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Design and Evaluation of a Fiber Optic Probe as a means of Subsurface Planetary Exploration

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DESIGN AND EVALUATION OF A FIBER OPTIC PROBE AS A MEANS OF SUBSURFACE PLANETARY EXPLORATION
Design and Evaluation of a Fiber Optic Probe as a means of Subsurface Planetary Exploration

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Space and Planetary Science

by

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ABSTRACT

The Optical Probe for Regolith Analysis (OPRA) is an instrumentation concept designed to provide spectroscopic analysis of the near subsurface of unconsolidated regolith on bodies such as moons, asteroids and planets. Below a chemically altered surface may lay the geological history in the form of stratigraphy that is shielded from degradation due to harsh external environments. Most of what we know about our solar system comes from remote platforms, such as satellites that are deployed into orbit around the target body. In the case of Mars, we have had several successful landers and rovers however, with the exception of the Mars Science Laboratory that just drilled its first hole, the complexity of subsurface excavation has limited the extent of subsurface exploration to simple scoops deployed on the ends of robotic arms which, by their very nature, will erase any stratigraphy that it may be digging into.

The OPRA instrumentation concept allows for an integrated, lightweight and simple apparatus for subsurface exploration via a small, spike like structure which contains integrated optical fibers coupled to small windows running down the length of the probe. Each window is connected to a spectrometer housed onboard the deploying spacecraft. Each window is separately interrogated via the spectrometer over the wavelength range 1–2.5 μm to produce a spectroscopic profile as a function of depth.

This project takes the Technology Readiness Level (TRL) of the OPRA instrumentation concept to level 3, which is defined by NASA to be the demonstration either analytically or
experimentally of the proof of concept for critical functions of the proposed instrument. Firstly, to demonstrate that optical fibers are feasible for this type of application, we report on the techniques used by NASA to space qualify optical fibers. We investigate the optical performance of several fiber optic bundle configurations, both experimentally and numerically, to help optimize bundle performance. Optical bundles were then spectrally validated via a series of spectral comparisons between standardized reflectance spectroscopy targets and spectra obtained with the bundles. We also report on the integration of fiber optical bundles into other research and experimental results from several other groups within our research teams to obtain spectra under a more “space like” environment. Finally, the probe housing structural performance was investigated via finite element analysis, using probe penetration forces derived from data analysis of experimentation conducted by the Apollo lunar missions, and investigations into a mechanical analogue for the Martian regolith.
ACKNOWLEDGMENTS

First and foremost, I would like to thank my adviser, Dr. Rick Ulrich; none of this would have been possible without your guidance and patience. You flexibility and advice have greatly been appreciated over the years. I would also like to thank my committee members, Dr. Mark Arnold, Dr. Larry Roe and Dr. John Dixon, who have also helped guide me on this journey!

I would also like to acknowledge one of my REU student, Margaret Raabe who worked under me for a summer and whose experiments were very helpful for my work on icy regolith spectra.
DEDICATIONS

I would like to dedicate this to my mum, Cindy, my brothers Chris and David and my sister, Elise. I hope in some way I have helped you see that the only limits in life are those which we place on ourselves.

To my Spanish brother, Pedro Llanos; we made it! You played no small part in this accomplishment my friend, while we may be miles away; you have been here with me every step. We reap what we sow, and finally, we both have some harvest for our days, weeks and years of hard work.

Last, but not least, a sincere thank you to Darryl and Lynn, my Karate instructors, who took me under their wings at 12 years of age. Without a shadow of doubt, my highest accomplishment in life has been the years of training and competing at a national level and earning my 3rd degree black belt. No club I have seen comes even close to the standards you hold your students too, and the level to which those who decide to take it seriously are trained. Simply put, I would not be anywhere near where I am in life without your guidance, in and out of the class, and for that I am eternally grateful. To my friend; Pete thanks for believing in me…. We made it!
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<tr>
<td>APXS</td>
<td>Alpha-Proton X-Ray Spectroscopy</td>
</tr>
<tr>
<td>BRDF</td>
<td>Bi-directional Reflectance Distribution Function</td>
</tr>
<tr>
<td>CAT</td>
<td>Crew Aid Tool</td>
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<tr>
<td>DEM</td>
<td>Digital Elevation Models</td>
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<tr>
<td>ESAS</td>
<td>Exploration Systems Architecture Study</td>
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<tr>
<td>FOB</td>
<td>Fiber Optic Bundle</td>
</tr>
<tr>
<td>FT-IR</td>
<td>Fourier Transform Infrared Spectrometer</td>
</tr>
<tr>
<td>IRTM</td>
<td>Infrared Thermal Mapper</td>
</tr>
<tr>
<td>IRM</td>
<td>Infrared Thermal Mapper</td>
</tr>
<tr>
<td>ISRU</td>
<td>In Situ Resource Utilization</td>
</tr>
<tr>
<td>JSC Mars 1</td>
<td>Johnson Space Center Martian simulant</td>
</tr>
<tr>
<td>LIBS</td>
<td>Laser Induced Breakdown Spectrometer</td>
</tr>
<tr>
<td>LOLO</td>
<td>Lunar Orbiter Laser Altimeter</td>
</tr>
<tr>
<td>LPSC</td>
<td>Lunar and Planetary Science Conference</td>
</tr>
<tr>
<td>LR</td>
<td>Laser Ranging</td>
</tr>
<tr>
<td>LRO</td>
<td>Lunar Reconnaissance Orbiter</td>
</tr>
<tr>
<td>MSL</td>
<td>Mars Science Laboratory</td>
</tr>
<tr>
<td>NA</td>
<td>Numerical Aperture</td>
</tr>
<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
</tr>
<tr>
<td>NEPP</td>
<td>NASA Electronic Parts &amp; Packaging Program</td>
</tr>
<tr>
<td>OPRA</td>
<td>Optical Probe for Regolith Analysis</td>
</tr>
<tr>
<td>TES</td>
<td>Thermal Emission Spectrometer</td>
</tr>
<tr>
<td>THEMIS</td>
<td>Thermal Emission Imaging System</td>
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Equation 2: Critical Angle .................................................................................................. 14
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CHAPTER 1 INTRODUCTION

1.1 Statement of Problem

This research was a feasibility study for the Optical Probe for Regolith Analysis (OPRA) which was designed to enable the near subsurface spectroscopic analysis of unconsolidated regolith on planetary bodies. This probe utilizes optical fibers integrated into a small, spike like structure, with a series of windows running down its shaft. Each window is coupled to a spectrometer housed onboard the deploying spacecraft. Once the OPRA instrument is inserted into the subsurface, each window is interrogated via a spectrometer, providing in-place spectroscopic analysis without the need for complex excavation, trenching or scooping.

The initial OPRA concept is illustrated in Figure 1; here we see a spike like structure approximately 5 cm in diameter and 61 cm long. It is the purpose of this research to take this concept to a technology level of 3 as defined by NASA.

1.2 Research Motivation

Solar system exploration has entered a phase in which subsurface exploration is playing an increasingly important role. Beneath the chemically altered surface of a planetary body may lay evidence of past life, keys to the geological evolution of the planet, and in the case of the Moon and Mars, possible resources which may one day be harnessed to sustain manned missions. Mars
has been extensively investigated via satellites to reveal various global trends of subsurface ice distribution, surface topology and thermal properties. Landers and rovers allow for a much more localized investigation such as spectroscopic analysis using techniques such as X-Ray Fluorescence (Clark et al., 1977), Alpha-Proton X-Ray Spectroscopy (APXS) (Rieder, 1997), Mossbauer Spectroscopy, Thermal Emission Spectroscopy (P.R. Christensen et al., 2003) and the Laser Induced Breakdown Spectrometer (LIBS), on board the Mars Science Laboratory (MSL).

Figure 1: Illustration of initial OPRA concept (adapted from image provided by Ulrich)
All of these techniques essentially have the same limitations; that is, they are sensitive to only the first few microns of the target’s surface, which limits our understanding of subsurface processes and the geologic history of the planet. For any extensive manned missions to the Moon or Mars, we need to utilize indigenous resources; this is identified (Sanders & Duke, 2005) by the NASA as one of the crucial areas of research that needs to be pursued with respect to the long term goal of manned missions to other planets (Figure 2). In situ resource utilization (ISRU) would allow manned missions to harvest resource from the surface, subsurface and atmosphere to produce fuel, water, propellant etc. thus reducing the needed mass that must be delivered from the Earth. Although mankind may be a long way from extensive manned missions, the next step towards this goal is to gain a better understanding of the possible resources we may encounter beneath the surface on the Moon and Mars.

This work demonstrates the feasibility of a subsurface spectroscopic probe, designed to be used either via astronauts as a hand held tool or operated remotely from a lander or rover. These spacecraft will allow quick and easy spectroscopic analysis of subsurface stratigraphy of planetary bodies without the need for complex excavation, trenching or scooping. This instrument will preserve the subsurface layering structure, thus preserving the geological history of the target body.
1.3 Planetary Exploration

Much of what we currently know about our solar system comes from remote, orbital platforms that rely on signal analysis of electromagnetic radiation interactions at the surface of the planetary body. From a geological and mineralogical perspective, infrared spectroscopy represents one of the best observational wavelengths in which to observe. Features related to, but not limited to, vegetation, soil moisture content, silicates and clays are most easily observed within this spectral region. With regards to Mars, there have been several orbital platforms that have made observations in this spectral region of the surface. The Mariner 9 orbiter (McCauley et al., 1972), which launched in 1971, contained the Infrared Interferometer Spectrometer, which
operated over a spectral range of 6 – 50 μm. The Viking mission orbiters, launched in 1975, contained the Infrared Thermal Mapper (IRTM) which operated over a spectral range of 6 – 50 μm. The Mars Global Surveyor (Bandfield, Hamilton, & Christensen, 2000), which launched in 1996, contained the Thermal Emission Spectrometer (TES) spectrometer which operated over a spectral range of 6 – 50 μm. Mars Odyssey (Philip R Christensen et al., 2003), which launched in 2001, contained the Thermal Emission Imaging System (THEMIS) spectrometer which operated over a spectral range of 2.5 – 5 μm. Mars Express, which launched in 2003, contained the Visible and Infrared Mineralogical Mapping Spectrometer (OMEGA) which operated over a spectral range of 0.5 – 5.2 μm.

1.3.1 Remote Sensing

Remote sensing is generally sensitive to only the top most layer of the surface, typically only the first few microns and this does not necessarily give an accurate representation of what is underneath the surface. As with all planetary surfaces, the chemical, mineralogical and biological conditions can change as a function of time. Locally caused alterations such as geological activity, including plate tectonics, volcanism, fluid flow and eolian processes can cause surface alterations. Surface alterations may also occur due to regular weather (much in the same way as Earths weather can change our surface) and also external processes, such as meteorite impacting and space weathering. Much of what we know about the solar system comes from remote sensing, which, as already stated, is sensitive to the very top layer of the target body. When we perform remote sensing we are viewing a body as it currently is, and can only speculate as to the geological history by drawing analogies to our own understanding regarding our planet. To fully understand the geological processes, both past and present, it will be necessary to directly access
and investigate the subsurface. Manned missions to other planetary bodies are a long way off, and before we can even attempt such a mission, not only must we have a thorough understanding of the target planetary body’s history but also have detailed knowledge of the available planetary resources that can be utilized by the mission crew.

1.3.2 Geological History

Stratigraphy is the process by which newer layers of materials are deposited on top of older layers via ongoing geological activity on a planetary surface. This subsurface layering structure provides a geological history of a planetary body, which is well preserved below the subsurface, away from any surface alterations that may occur. In order to build an accurate geological history profile using the technique of stratigraphy it is important to access these layers with minimal disturbance. Coring is one such technology that allows the preservation of subsurface laying structure; it involves driving a hollow tube into the surface to the desired depth and then removing this tube (with the subsurface occupying the once hollow space). Once the corer instrument is retracted, the complete, intact sample is removed and analyzed. This technique was used on the lunar missions but was not automated; instead, the astronauts hammered the corer instrument into the lunar regolith as shown in Figure 3, with limited success. Currently, we are at least several years away from having a truly autonomous instrument, capable of drilling or coring into extraterrestrial surfaces; Dr. Khris Zacny, one of the foremost robotic experts in the field of autonomous subsurface robotic exploration, has a complete in-depth analysis of this area of research in his book and publications (Bar-Cohen & Zacny, 2009)
Figure 3: i) An astronaut testing out the lunar core sampling instrument on Earth. ii) Actual image of a core sample being taken on the lunar surface. iii) Actual lunar core. (source for all images (Allton, 1989)).
1.3.3 Search for Evidence of Past or Present Life

A combination of the current low temperatures, lack of liquid water, low atmospheric pressure and the high levels of UV radiation at the Martian surface means that the chances of any life forms existing on top of the regolith are highly unlikely (Clark, 1998). The average planet wide surface temperature is about -73 C (220 K), and the average atmospheric pressure is about 6 mbar, which makes the existence of pure liquid water unlikely for any prolonged period of time on the surface; however, with the addition of certain chemicals, it is possible to lower the freezing point of water into this range. Experiments conducted within our lab at the Arkansas Center for Space and Planetary Sciences (Chevrier & Altheide, 2008) show that brines can maintain their liquid state to much lower temperatures (typically down to 205K) than pure water. Not only do brines lower the freezing point of water, but they also reduce the evaporation rate (Sears & Chittenden, 2005), thus increasing the possible residency time in the liquid state. Numerical models (Ulrich, Kral, Chevrier, Pilgrim, & Roe, 2010) indicate that there could be locations within the near surface regolith warm enough for certain brines to exist for several hours per day for a large majority of the Martian year. These potential areas of liquid brine represent possible locations where life may have once existed, and carrying out *in situ* investigations in these areas represents a top priority in our search for past or present life. For example, at the Mars Pathfinder landing site, it was estimated that we would expect a temperature above -73 C (220 K) for the majority of the year at depths of approximately 4 cm.
1.3.4 Resource Identification

Manned missions to Mars and any extended stay missions to the Moon will require us to utilize indigenous resources to help reduce the amount of cargo that must be transported to support the crew during the duration of the mission. NASA identifies the field of *In Situ* Resource Utilization (ISRU) as a mission critical research area in their Exploration Systems Architecture Study (ESAS). In order to fully research and develop ISRU, a much greater understanding of the lunar and Martian subsurface is needed, and it is the purpose of this research to demonstrate the feasibility of an OPRA type instrument to help facilitate this. The four main areas of ISRU, identified by NASA (Stanley, Cook, & Connolly, 2005) as potential benefit to manned missions, are shown in Table 1 and Figure 4. Whilst all of these technologies are still in the early stages of development, it is clear that NASA has a need to explore the subsurface in a much greater detail than has been completed to date.

Table 1: Overview of NASA identified ISRU areas. Adapted from NASA’s *In Situ* Resource Utilization (ISRU) Capability Roadmap Final Report, 2005.

<table>
<thead>
<tr>
<th>ISRU Area</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mission consumable</td>
<td>Propellants, fuel cell reagents, life support consumables, and feedstock for manufacturing &amp; construction</td>
</tr>
<tr>
<td>Surface construction</td>
<td>Radiation shields, landing pads, walls, habitats, etc.</td>
</tr>
<tr>
<td>Manufacturing and repair</td>
<td>Spare parts, wires, trusses, integrated systems etc.</td>
</tr>
<tr>
<td>Utilities</td>
<td>Solar power</td>
</tr>
</tbody>
</table>
Figure 4: Image taken of a trench being excavated via the robotic arm of the Mars Phoenix mission. Here subsurface ice is clearly revealed underneath the Martian regolith, this could potentially be a source of water, oxygen and hydrogen (source NASA).

1.4 Optical Probe for Regolith Analysis Concept

As detailed above, accessing the undisturbed and unaltered subsurface of a planetary body is critical in helping us address if life once existed and in helping us identify any indigenous resources we may be able to utilize. OPRA is a small, spike like instrument, designed to either be attached to a robotic instrument, such as a lander or rover, or as part of a portable hand held instrument such as a Crew Aid Tool (CAT). OPRA has a series of windows running down the length of its shaft which are individually coupled, via optic fibers, to an IR spectrometer. This spectrometer is housed in the deploying spacecraft or, in the case of the CAT deployment method, is housed in a portable “box” that is carried by an astronaut. Here, we demonstrate that the OPRA instrument is a feasible, small, lightweight, simple and relatively inexpensive instrument that could be comprised from largely already space qualified components. This probe is both scalable and highly customizable to the needs of the individual mission requirements.
1.5 Technology Readiness Level

The Technology Readiness Level (TRL) is a systematic measure used by NASA (Mankins, 1995) to determine the current level of instrument development relative to the ultimate goal of a completely functional product that has undergone rigorous testing in the expected working conditions (Table 2). Under this research OPRA was developed to a TRL of 3; here, we will demonstrate all evidence supporting this classification.

Dissertation Organization

Chapter 2 gives an overview of some basic concepts regarding optical fibers and also reviews some of the main missions that have incorporated optical fibers, as well as the rigorous space qualification process optical fibers have undertaken. Chapter 3 introduces the OPRA probe and gives a review overview of the Nicolet 6700 spectrometer and the fiber port that allows us to take reflectance spectra. Chapter 4 reviews the experimental procedures and results used to characterize several characteristics of fiber optic bundles. Chapter 5 discusses the numerical model that was used to help optimize probe performance. Chapter 6 discusses the spectroscopic performance of fiber optic bundles in comparison to standard reflectance spectra. This chapter also discusses spectra obtained within the University’s Andromeda chamber taken at conditions similar to Saturn’s moon Titan. Chapter 7 deals with structural analysis of the probes housing, using finite element analysis to ensure that the probe can survive the insertion and penetration into a planetary surface. Chapter 8 presents conclusions and suggests future work, followed by the appendix which also contains a list of all publications, and conference proceedings pertaining to this project.
Table 2: Technology Readiness Level (TRL) as determined by NASA (adapted from (Mankins, 1995)).

<table>
<thead>
<tr>
<th>TRL</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Basic principles observed and reported: Transition from scientific research to applied research. Essential characteristics and behaviors of systems and architectures. Descriptive tools are mathematical formulations or algorithms.</td>
</tr>
<tr>
<td>2</td>
<td>Technology concept and/or application formulated: Applied research. Theory and scientific principles are focused on specific application area to define the concept. Characteristics of the application are described. Analytical tools are developed for simulation or analysis of the application.</td>
</tr>
<tr>
<td>3</td>
<td>Analytical/ experimental critical function and/or characteristic proof-of-concept: Proof of concept validation. Active Research and Development (R&amp;D) is initiated with analytical and laboratory studies. Demonstration of technical feasibility using breadboard or brass board implementations that are exercised with representative data.</td>
</tr>
<tr>
<td>4</td>
<td>Component and/or breadboard validation in laboratory environment: Standalone prototyping implementation and test. Integration of technology elements. Experiments with full-scale problems or data sets.</td>
</tr>
<tr>
<td>5</td>
<td>System/subsystem/component validation in relevant environment: Thorough testing of prototyping in representative environment. Basic technology elements integrated with reasonably realistic supporting elements.</td>
</tr>
<tr>
<td>6</td>
<td>System/subsystem model or prototype demonstration in a relevant environment: Prototyping implementations on full-scale realistic problems. Partially integrated with existing systems. Limited documentation available. Engineering feasibility fully demonstrated in actual system application.</td>
</tr>
<tr>
<td>7</td>
<td>System prototype demonstration in a space environment: System prototyping demonstration in operational environment. System is at or near scale of the operational system, with most functions available for demonstration and test. Well integrated with collateral and ancillary systems. Limited documentation available.</td>
</tr>
<tr>
<td>8</td>
<td>Actual system completed and “flight qualified” through test and demonstration: End of system development. Fully integrated with operational hardware and software systems. Most user documentation, training documentation, and maintenance documentation completed. All functionality tested in simulated and operational scenarios. Verification and Validation (V&amp;V) completed.</td>
</tr>
<tr>
<td>9</td>
<td>Actual system “flight proven” through successful mission operations: Fully integrated with operational hardware/software systems. Actual system has been thoroughly demonstrated and tested in its operational environment.</td>
</tr>
</tbody>
</table>
CHAPTER 2 SUITABILITY OF OPTICAL FIBERS
FOR SPACE BASED APPLICATIONS

The first section of this chapter will briefly cover the basic theory of optical fibers and will review some of the fundamental physical characteristics that are relevant to this research. The second section will review several past space-based missions that utilized optical fibers and also will review the process of qualifying optic fibers for service in space.

2.1 Optical Fiber Characteristics

2.1.1 Total Internal Reflection & Snell’s Law

Total internal reflection can be understood through Snell’s law, Equation 1, which describes how a light ray acts when it encounters a boundary between two materials. A proportion of the light may be reflected and a portion may be refracted as shown in Figure 5. Here we see three light rays striking the boundary between material 1, whose refractive index is \( n_1 \), and material 2, whose refractive index is \( n_2 \). Ray ‘i’ (from Figure 5) strikes the boundary at a right angle, and is completely transmitted through to material 2 with no reflection or refraction. Ray ‘ii’ has a portion of its light reflected and refracted (when passing into a material with a higher refractive index light is refracted away from the normal). Ray ‘iii’ has no refraction component; instead, we have all the light being reflected back into material 1.
The critical angle is defined as the angle at which total internal reflection will first occur; any light ray striking the boundary below this critical angle undergoes total internal reflection. This critical angle is determined by setting $\theta_2$ to an angle of 90 degrees in Equation 1 and solving for $\theta_1$ to give Equation 2.

Equation 1: Snell’s Law

$$n_1 \cos \theta_1 = n_2 \cos \theta_2$$

Equation 2: Critical Angle

$$\theta_{critical} = \sin^{-1}\left(\frac{n_2}{n_1}\right)$$

Where $n_1$ and $n_2$ refractive index of material 1 and material 2

$\theta_1$ and $\theta_2$ are the angle of incidence and angle of refraction (from the normal)

2.1.2 Modal Dispersion

As a signal travels along an optical fiber it tends to disperse or distort as a result of signal path differences within the fiber. Elements of the same signal may enter the fiber at slightly different angles (referred to as modes), resulting in slightly different path lengths for the modes of the same signal. The resulting variation in path lengths cause the signal to be distorted as it exits the fiber. The two types of modal dispersions are reviewed below.

- **Intermodal Dispersion**: Consider two light rays that enter an optical system as shown in Figure 7 i); both rays enter the system at the same time. Ray i enters directly along the
central axis; ray ii enters the fiber at an angle of $\theta_2$. Ray ii will exit the fiber at a slightly different time than ray i as a result of its greater path length through the fiber. This “zigzagging” is the cause of intermodal dispersion resulting in a spreading of the original signal, as is seen by comparing the input to the output pulse.

- **Intramodal Dispersion:** Even a signal exiting a single mode fiber (defined in 2.1.5) still undergoes a small amount of dispersion, resulting in a spreading of the original signal. All periodic signals can be decomposed via the Fourier transform, into various component waves, which are centered on the spectral mean of the original signal. As these waves pass through the optic fiber, the various wave components will undergo path differences, much the same but to a lesser extent, as multimodal signals.

![Figure 5: Illustration of light interaction with a flat, plane surface. Light undergoing complete transmission i), light partially refracted and partially reflected ii), light undergoing total internal reflection iii).](image)

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2.1.3 Numerical Aperture

The Numerical Aperture (NA), Equation 3, is used to describe the maximum acceptance angle of a light ray entering an optical fiber that undergoes total internal reflection. It is not to be confused with the critical angle, although, they are closely related. The critical angle describes the angle at the core-cladding boundary where total internal reflection occurs and the maximum acceptance angle is the angle of a ray crossing over the air-core boundary ($\theta_{\text{max}}$) that produces the critical angle ($\theta_{\text{critical}}$) at the core cladding boundary as shown in Figure 6.

Equation 3: Numerical Aperture

$$NA = \sqrt{n_{\text{core}}^2 - n_{\text{cladding}}^2}$$

Figure 6: Illustration of a ray light entering at the maximum acceptance angle into an optical fiber. This ray is refracted from its original angle of $\theta_{\text{max}}$ to an angle of $\theta_r$ which strikes at the core-cladding boundary at the critical angle $\theta_{\text{critical}}$. 

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2.1.4 Bend Radius

Optical fibers will experience a decrease in optical performance and possible physical damage when bending beyond their bend radius limit. All fibers come with a recommended bend radius which should be strictly adhered to, ensuring optimal optical performance and fiber integrity throughout a fiber’s lifetime.

2.1.5 Optical Fiber Types

There are three main types of optical fibers used in industry today (Figure 7); each suited to a different type of application. Optical fibers generally work on the principle of total internal reflection which is achieved by having a core surrounded by a cladding of a different refractive index as previously discussed. The three main types of fibers are:

- **Multimode step-index optical fibers:** Fiber of choice for this research, these fibers, Figure 7 i), have a core of a single refractive index surrounded by a cladding of a higher refractive index; these types of fibers have the highest range of NA (typically 0.2-0.52).

- **Graded-index optical fibers:** These have cores with a radially-varying refractive index. Their purpose is to reduce modal dispersions by reducing the path difference between a signal as it propagates through a fiber (Figure 7 ii).

- **Single-Mode optical fiber:** These have a very small diameter core, surrounded by a cladding and are designed to almost completely remove model dispersion and have a very small NA (Figure 7 iii).
Figure 7: Comparison of signal path, input and output signal for i) multi-mode step index fiber, ii) a graded index optical fiber and iii) a single mode optical fiber.
Optical fibers have over 30 years of proven spaceflight heritage (Melanie N Ott, 2010) and, to this date, have never failed or been significantly damaged during a mission. They were initially used to transmit information within the spacecraft much in the same way as they are used in the telecommunication industry today, but with the progression of technology, they have evolved into key components within several optical instruments as shown in the below table.

Table 3: Several missions that have utilized optical fibers either to transmit data or as part of an optical system (adopted from (Melanie N Ott, 2010)).

<table>
<thead>
<tr>
<th>Project Name</th>
<th>Year</th>
<th>Fiber Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar Magnetospheric Particle Explorer</td>
<td>1992</td>
<td>Command Transmission</td>
</tr>
<tr>
<td>X-ray Timing Explorer</td>
<td>1995</td>
<td>Command Transmission</td>
</tr>
<tr>
<td>Microelectronic and Photonic Test Bed</td>
<td>1997</td>
<td>Command Transmission</td>
</tr>
<tr>
<td>Hubble Space Telescope (upgrades)</td>
<td>1997</td>
<td>Command Transmission</td>
</tr>
<tr>
<td>Tropical Rainforest Measuring Mission</td>
<td>1997</td>
<td>Command Transmission</td>
</tr>
<tr>
<td>Microwave Anisotropy Probe</td>
<td>2001</td>
<td>Command Transmission</td>
</tr>
<tr>
<td>Geoscience Laser Altimeter</td>
<td>2003</td>
<td>Optics</td>
</tr>
<tr>
<td>Mercury Laser Altimeter</td>
<td>2004</td>
<td>Optics</td>
</tr>
<tr>
<td>Shuttle-Return-to-Flight</td>
<td>2004</td>
<td>Optics</td>
</tr>
<tr>
<td>Lunar Reconnaissance Orbiter</td>
<td>2009</td>
<td>Optics</td>
</tr>
<tr>
<td>Mars Science Lab ChemCam.</td>
<td>2012</td>
<td>Optics</td>
</tr>
</tbody>
</table>
2.2.1 NASA Research on Optoelectronics

The NASA Electronic Parts & Packaging Program group (NEPP) performs research on optoelectronics and are responsible for assuring that new and emerging technologies that utilize optoelectronics are fully tested and are space qualified (Barnes, Ott, Becker, & Wright, 2005). The NEPP program defines the following as an adapted table that shows the main (Barnes et al., 2005) phases for a typical Mars surface mission; each must be addressed when testing new technologies to ensure they will survive the anticipated environment.

Table 4: Typical phases of a Mars mission that all sub-components must be able to survive. All components are tested in each of the mission phases shown in this table.

<table>
<thead>
<tr>
<th>Mission Phase</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-Launch/Launch</td>
<td>Storage, shock and vibration, moisture ingress. Total dose effects due to passage through belts.</td>
</tr>
<tr>
<td>Transit</td>
<td>Aging effects, total dose effects due to flares. Single event effects from GCR and flares. Thermal cycling, outgassing.</td>
</tr>
<tr>
<td>Mars Orbit/Descent</td>
<td>Shock and vibration, charging effects in ionosphere. Total dose effects single event effects, parachute failure.</td>
</tr>
<tr>
<td>Mars Surface</td>
<td>Wind &amp; dust, contamination thermal cycling low temperatures, single event effects, aging effects. Shock and vibration.</td>
</tr>
</tbody>
</table>
- **Radiation exposure**: This can adversely affect the attenuation profile of an optical fiber and this attenuation is a function of transmission wavelength, radiation dose and fiber temperature. Any impurities in the fiber tends to “color” the fiber (leading to reduction in performance) with increased exposure to radiation (M.N. Ott, 1998)(Barnes et al., 2005).

- **Thermal cycling**: Investigations (M.N. Ott, 1998) revealed two distinct effects of thermal cycling. Transient changes are caused by the thermal expansion and contraction as a fiber experience cycling temperatures. Permanent change occurs at very high temperatures, and the belief is that this is the result of the:

  "....extrusion process for depositing these materials on top of an optical fiber induces stresses that tend to relax and result in shrinkage at high temperature extremes."

(Quoted from Fiber optic cable assemblies for space flight II: Thermal & radiation effects (Melanie. Ott, 2010)). To mitigate problems associated with permanent changes in optical fibers, all flight cables are “pre-shrunken” by placing them in an extreme temperature for a prolonged period of time.

- **Vacuum exposure**: This produces outgassing in materials that can lead to changes in the transmission profile of a fiber. To mitigate this problem fibers are placed into a vacuum chamber for a prolonged period of time, and then hermetically sealed.
2.2.2 Mars Science Laboratory Optical Fibers

A wide variety of optical fibers and bundles have been extensively investigated for the three main effects of the harsh space environment and are detailed above. The most recently launched instrument to utilize optical fibers is the Mars Science Laboratory’s (MSL) Laser Induced Breakdown Spectrometer (LIBS), which is part of the ChemCam suite of instruments. These fibers were extensively tested and space qualified (Lindensmith et al., 2010) to the harsh conditions on the Martian surface. This multimode, 5.7 m length, 300 μm core diameter optical fiber connects the signal received from the telescope of the LIBS instrument to the onboard spectrometer housed in the body of the rover, as shown in Figure 8. The specific optical fiber qualifications for this mission involved the following:

- Motion life testing, attenuation vs. motion and temperature
- Radiation testing
- Planetary protection (oven baked for 50 hours at 190C to remove any contaminants)
- Thermal cycling
- Cable vibration, connector vibration
- Packaging qualification and verification
Figure 8: Illustration of the LIBS instrument onboard the MSL, highlighting the use of optical fibers in the harsh environment on the surface of Mars. (images adapted from (M.N. Ott et al., 2009))
2.2.3 Lunar Reconnaissance Orbiter Optical Fibers

The Lunar Reconnaissance Orbiter (LRO) contains several sets of Fiber Optic Bundles (FOB’s) and are utilized in the Lunar Orbiter Laser Altimeter (LOLA) and the Laser Ranging (LR) instrument. The LR instrument is able to calculate very accurately the distance from the satellite to the Earth, as it orbits the moon. LOLA utilizes the same, time stamped laser pulses received by the LRO to make accurate surface measurements of the Moon as described in Figure 9. The FOB in the antenna is a 7 channel, “6 around 1” configuration as shown in Figure 9.1; this 10 m long FOB has multimode step index fibers of 0.22 NA with a core diameter of 400 μm. The LRO receives a laser signal from Earth directed to the top of its antenna as shown by label “a”. This signal focuses into the FOB and transmitted through the fibers “b” and into the spacecraft housing “c”. The LR instrument uses part of this signal, while the rest transmits onto the lunar surface through the LOLA instrument “d”. The signal strikes the lunar surface and reflects back up into the LOLA detector, “f”. The time delay of the reflected signal is used to produce detailed Digital Elevation Models (DEM) of the surface. Figure 9.2 is an image of the antenna with the FOB identified “g”, Figure 9.3, “i” is a close up of the 7 channel FOB. (images adapted from (Ramos-Izquierdo et al., 2009) )

2.3 Summary

One major design consideration that will be discussed in later chapters is the fibers bend radius, which could severely restrict the compactness of the final probe design. Optical fibers and fiber optic bundles have undergone rigorous space qualification, and to this date have not failed whilst in a space application.
Figure 9: i) Illustration of the LRO which utilizes optic fibers in both the LOLO and the LR instruments. ii) A picture of the antenna of this instrument, and iii) is a close up shot of the seven channel space qualified, fiber optic bundle (adapted from (Ramos-Izquierdo et al., 2009)).
CHAPTER 3 THE OPTICAL PROBE FOR REGOLITH ANALYSIS

OPRA is an instrumentation design concept to perform spectroscopic analysis either on or below a planetary surface, with no need to perform digging, excavation or trenching. OPRA can be utilized via a robotic arm; for example, on a lander or rover, or used as a standalone Crew Assist Tool (CAT) to help in the exploration of the subsurface. As discussed in Chapter 7, some of the past Apollo missions incorporated instruments that allowed astronauts to extract complete subsurface cores; the cores were returned to Earth for further analysis. Subsurface cores allow for the preservation of subsurface layers, however core extraction, while relatively simple for humans to perform, and is a non-trivial task to perform autonomously. Other geological sampling tools include scoops, rakes, hammers, drills and tongs; all of which, with the exception of the corer, are unable to maintain any stratigraphy that may be present.

3.1 Initial Concept

The initial OPRA probe concept is shown in Figure 1; here we see a spike like instrument composed of a hollow 5 cm diameter, 60 cm long tube with a series of windows running down one side of its shaft. Each window is coupled to a Fourier Transform Infrared Spectrometer (FT-IR) via a pair of optical fibers with a proposed transmission range of 0.5-5 μm. OPRA is pushed into a planetary subsurface to the required depth and, once inserted, material directly in contact with each of the windows has its spectra acquired independently of the other windows. This provides a spectroscopic profile as a function of depth. At the top of the probe is a stop plate
which also contains four windows which allow spectra of the surface to be acquired at the same time as the subsurface. All fibers are routed to an FT-IR spectrometer housed inside the body of the deploying spacecraft via an optical switch. The FT-IR spectrometer is isolated within the spacecraft, which protects it from the harsh space environment, improving its reliability and stability. Within the OPRA instrument there are no moving parts or electronics, and a high level of redundancy due to multiple optical fibers and windows. In order to successfully demonstrate a TRL 3, three main objectives of this work were identified:

- **Investigation of the optical train**: This is concerned with optimizing the ratio of the signal transmitted from the FT-IR spectrometer to the signal received by the FT-IR spectrometer detector.

- **Investigation of mechanical issues**: This addresses the physical stresses and strains that OPRA may be subjected to as it is penetrated into the subsurface, as well as potential window damage from regolith abrasion. The size and thickness of the probe must be such that it can survive the anticipated penetration forces that it may undergo on Mars.

- **Spectral demonstration**: Spectra was taken from a range of materials that we know currently exist on the Martian surface. These spectra were used to build a small spectral library that are used for comparison to standard reflectance spectra.
3.2 Nicolet 6700 Spectrometer

The Nicolet 6700 FT-IR Spectrometer (Figure 10) is a research grade, multipurpose, highly customizable spectrometer manufactured by ThermoScientific. It is the most important instrument used for this work. The spectral range for this research is between 0.5 – 5 μm, which requires the instrument to be configured in the following manner.

- **Light Source**: White Light
- **Detector**: TEC InGaAs
- **Beam Splitter**: Quartz

3.3 Standard Reflectance Spectroscopy

To obtain standard reflectance spectra from a solid/powdered sample with this instrument, the sample must be placed in the sample bay (labeled ”c” in the below image). Once the sample is presented, the instrument directs a signal onto the sample and processes the reflected signal to determine its spectra. Optical fibers allow us to both take this signal and redirect it to another location of our choosing, and collect the reflected signal and guide that back onto the detector. Optical fibers have very low attenuation rates, meaning that signals can travel large distances with very little signal loss of distortion.

3.4 Fiber Port

The fiber port (Figure 11) is placed into the sample bay (labeled c) in the below image. The port contains a pair of industry standard SMA-905 connectors; once the fiber port is inserted into the FT-IR spectrometer, the transmitted signal from the instrument is rerouted through the fiber port up into the first connecter and into the optical fiber(s). This signal emerges from the end of the FOB and illuminates the sample. The signal reflects from the sample back up into the receiving
fibers in the common end of the probe and is then reintroduced into the instrument's detector (label d, below image).

Figure 10: Nicolet 6700 spectrometer with the instrument lid removed. Here, the light source, a), is guided through the beam splitter, b). Half the signal emerges from the beam splitter and is guided towards the sample. The attachment bay, c), is designed to allow both transmission (which is illustrated) and reflectance experiments by simply slotting the correct attachment into the bay. In the case of this research an optical fiber port is inserted into this equipment bay. The final signal is guided into the detector, d), for processing.
Figure 11: Fiber port coupled to a custom made fiber optic probe. This port is slotted into the FT-IR spectrometers equipment bay, and guides the instruments signal, a), into the optical fibers via a SMA-905 connector, b). This signal emerges from the common end of the probe, c), and is partly reflected back up into the common ends receiving fibers after striking the sample. These fibers connect back to the fiber port d) and the fiber port reintroduces this signal back into the instruments detector e).
3.5 Optical Train

3.5.1 Optical Fiber

The initially proposed spectral range of OPRA was specified as 0.5 – 5 μm; however, due to reasons that will be discussed shortly, the decision was made to use fibers that cover a range of 0.35 – 2.2 μm. This decision was made early on in the design process and was based upon three main points:

- **Cost:** IRphotonics are one of the few companies that are capable of producing optic fibers that can cover a spectral range of 0.3- 4.5 μm. These fibers are extremely hard to fabricate and represent the current state of the art in optical fibers over this spectral range. The costs of these fibers are $700 per meter of fiber. In comparison the cost of the Optran Ultra fibers were $60 per meter.

- **Turnaround Time:** The turnaround time ranged from 6-8 weeks for the optical fibers produced by IRphotonics; all fibers are custom made to order. Optran Ultra fibers had a turnaround time of ≈ 2-3 weeks.

- **Physical Requirements:** As shown in Table 5, IRphotonics fibers have very limited options with regard to physical performance characteristics in comparison to the Optran Ultra fibers. Most notably is the fibers small NA of 0.2 and the inability to bend. These physical restrictions are the result of fiber-cladding material and manufacturing process.
In comparison, Optran Ultra fibers provided by CeramOptec can be turned around in as little as two weeks and cost around $60 per meter. These fibers also have a much wider range of available physical performance characteristics, such as NA’s ranging from 0.2 – 0.53, a much smaller bend radius, and possible temperature ranges from 190 to 400 °C (83-673K). The Optran Ultra fiber is the fiber selected from the range of fibers CeramOptec can provide; this design decision came after a combination of experiments and numerical modeling into the optimization of fiber optic bundles that are discussed in the following chapters.

After carefully looking at the cost, turnaround time and the physical requirements of this project, Optran Ultra fibers manufactured by CeramOptec industries were the fiber of choice for this research (www.ceramoptec.com/filephotos/pdf/OptranUltra.pdf)

3.6 Fiber Optic Bundle

The purpose of using optical fibers in the OPRA probe is to allow the FT-IR spectrometer signal to illuminate subsurface regolith without the need for complex optical arrangements, such as mirrors, which are easily damaged or misaligned, or complex excavation of material from the subsurface. The final FOB design (discussed in more detail in Chapter 4) consists of Optran Ultra fibers with a NA of 0.53. The core diameters are 600 μm with a cladding diameter of 660 μm arranged in a tight, hexagonal packing configuration, which is similar to the space qualified FOB used onboard the LRO mission as previously discussed in Chapter 2. These fibers are the largest fibers that will fit into the ferule of the SMA-905 optical fiber connector in this configuration. The fiber configuration, fiber diameter and NA were determined to have the
highest light collection efficiency via a combination of numerical models and experimental results (Chapter 4).

Table 5: Optran Ultra and IRphotonics fiber specs. Here we note that even though the spectral range of the Optran Ultra fibers is below that initially proposed for OPRA, the pros for using this fiber far outweigh the reduction in spectral wavelength when compared to the IRphotonics fibers.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Optran Ultra</th>
<th>IRphotonics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiber Type</td>
<td>Step index multimode</td>
<td>Step index multimode</td>
</tr>
<tr>
<td>Numerical Aperture</td>
<td>0.53</td>
<td>0.2</td>
</tr>
<tr>
<td>Temperate Range</td>
<td>-40 to 100 C</td>
<td>-20 to 90 C</td>
</tr>
<tr>
<td>Core Diameter</td>
<td>600 μm</td>
<td>600 μm</td>
</tr>
<tr>
<td>Cladding Diameter</td>
<td>660 μm</td>
<td>700 μm</td>
</tr>
<tr>
<td>Breaking Radius</td>
<td>Not Specified</td>
<td>45 mm</td>
</tr>
<tr>
<td>Bend Radius (Short Term)</td>
<td>30 mm</td>
<td>Not Specified</td>
</tr>
<tr>
<td>Bend Radius (Long Term)</td>
<td>100 mm</td>
<td>Not Specified</td>
</tr>
<tr>
<td>Spectral Range</td>
<td>0.35 – 2.2 μm</td>
<td>0.3 – 4. μm</td>
</tr>
<tr>
<td>Cost</td>
<td>≈ $60 per meter</td>
<td>≈ $700 per meter</td>
</tr>
<tr>
<td>Turnaround Time</td>
<td>2-3 weeks</td>
<td>6-8 weeks</td>
</tr>
</tbody>
</table>
3.6.1 The Prism: Minimizing Probe Thickness

The purpose of the initially proposed method of allowing spectroscopic analysis of material adjacent to each of the probe windows was to directly couple the fibers to the windows. Due to optical fibers bend radius limit typically being 100 mm for the Optran Ultra fibers, it was not possible to directly couple the fibers to the windows as initially proposed without greatly changing the overall design and shape of the probe. In order to circumvent this problem, right angle prisms were investigated and shown to be a viable option for coupling the fibers to the windows of the probe. The prism of choice was a 3 mm, right angle prism made from BK7, which has a very consistent transmission range over the range of the optical fibers and is one of the most commonly used materials for technical applications over the 0.35 – 2.5 μm wavelength. BK7 was selected over the fused silica prisms due to its virtually flat transmission range, in contrast to fused silica which has two very distinctive regions of decreased transmission over the transmission range of the optical fibers. The windows of the probe consist of sapphire and are 1 mm in thickness. This material was selected because of its exceptional hardness and its almost flat optical transmission range. The window, coupled to the prism, gives a total optical path from the FOB tip to the sample (assumed to be in contact with the probe window) of 4 mm.

3.7 Probe Housing

The natural choice for the probe housing was titanium alloy due to its superior strength to weight ratio and resistance to corrosion and damage, all are essential qualities for space-based instrumentation. The final probe housing design and housing structural integrity research is discussed in Chapter 7.
3.8 Summary

OPRA is a small, spike like structure that allows in place subsurface spectroscopic analysis with minimal disturbance to any laying structure. The FOB’s that are at the heart of the design of this instrument connect to the Nicolet 6700 spectrometer via the fiber-port, which has a standard SMA-905 fiber optic connector. Due to the need to keep the cross sectional area of the probe as small as possible, it was necessary to introduce a small right angled prism to connect each FOB to windows in the probe. The natural choice for probe housing material was titanium due to its superior physical qualities previously discussed.

Figure 12: Illustration of the fiber port coupled to the spectrometer. Here both the transmitting and receiving fibers are exposed to the sample so that transmitted signal reflects from the sample and is then transmitted back up into the FT-IR spectrometer via the receiving fibers.
CHAPTER 4 FIBER OPTIC
BUNDLE CHARACTERISTICS

The purpose of this section is to determine FOB collection efficiency as a function of distance and as a function of FOB configuration. Results from this chapter were used to help develop and validate a numerical model of the expected power received by various fiber optic probes.

4.1 Minimizing Dead Space in a FOB

Optical fibers transmit and receive light through their cores, which are surrounded by a layer of non-transmitting cladding as previously discussed in Chapter 2. Dead space is defined as the total surface area which is unable to transmit or receive a signal (i.e. all other area apart from the core) while active space is defined as the total area of the fiber core within the FOB. It is assumed that all fibers in the FOB and are of the same diameter and arranged in a hexagonal fashion. The total number of fibers (all with the same fiber diameters) which can fit within a circular cross sectional area is a function of the number of rings of fibers surrounding the central fiber as described by Equation 4. Table 6 shows the results from this equation for the first three rings of a fiber optic bundle, and Figure 13 illustrates these three probes. Here, we see that the more fibers we have in a FOB, the less active area; hence the higher amount of surface area is wasted and not contributing to either transmitting or receiving the signal.
Table 6: Active area of a fiber optic bundle as a function of total number of fibers. Here we note that the larger the core diameters, the higher the active area, and the less space is wasted, for a hexagonal configuration as shown in the below image.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Total Number of Fibers</th>
<th>Core Diameter (µm)</th>
<th>Total Active Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>7</td>
<td>600</td>
<td>64.3%</td>
</tr>
<tr>
<td>b</td>
<td>19</td>
<td>360</td>
<td>62.8%</td>
</tr>
<tr>
<td>c</td>
<td>37</td>
<td>260</td>
<td>62.4%</td>
</tr>
<tr>
<td>Not Shown</td>
<td>61</td>
<td>202</td>
<td>62.2%</td>
</tr>
<tr>
<td>Not Shown</td>
<td>30,301</td>
<td>5E-03</td>
<td>60.8%</td>
</tr>
</tbody>
</table>

Figure 13: Illustration of three different fiber optic bundle configurations, which all occupy the same cross sectional surface area (i.e. surface area of SMA 905 connector). Shown here, the cores of the fibers are white and the cladding is dark grey. The cores transmit and receive signals and are designated as the active regions, all other areas are designated dead space. Image i), ii) and ii) have 7, 19 and 37 fibers respectively (image to scale) “r” represents the fiber radius; “R” represents the bundle radius.
Equation 4: Total fibers in hexagonal configuration

\[ Total \ Number \ of \ Fibers \ (N) = 1 + \sum_{a=1}^{a=r} 6a \]

Where \( r \) = number of rings around central fiber

4.2 Collection Efficiency

Collection efficiency is concerned with optimizing the transmitted signal to returned signal ratio to ensure the acquisition of the strongest return signal possible into the instruments. Collection efficiency was determined by the following set of experiments.

4.2.1 Experimental Set-Up

FOB efficiency was determined via the experimental set-up shown in Figure 14; shown here is a FOB coupled to the transmitting connector of the spectrometers fiber port labeled “a” in this figure. This signal is then guided through the FOB, “b”, and emerges from the common end of the probe to illuminate the sample, c). The sample in this experiment was a section of optical grade Spectralon, which has an albedo of 99% over the spectral range of 0.2 – 1.5 \( \mu m \) (Georgiev & Butler, 2007). The FOB-sample distance was varied via a translating post holder, “c”, which allows the sample to be moved very accurately over small distances. A portion of this reflected signal enters the receiving fibers and is guided through the probe to emerge onto the detector d). The detector (e) was a Newport 1916-C power meter and was set to record the power reading at the 1 \( \mu m \) wavelength range. The experiment was conducted in almost complete darkness with both the FOB common end and the detector being shielded from stray light. The experiment was
assembled upon an optical aluminum breadboard to ensure stability of the equipment once experiments were underway. The FOB-sample distances were measured via a pair of digital caliper (as shown in c). Table 7 details the five probe configurations that were investigated. Experiments 1 and 3 were conducted using probe 1, experiments 2 and 5 use probe 2, and experiment 4 uses probe 3 (note that probe 3 has a fiber configuration of 40 randomly arranged fibers, with 20 transmitting and 20 receiving fibers). Both probe 1 and 2 have the same configuration of a single fiber in leg one, six fibers in leg two and a six around configuration in the common end. Each experiment connects both legs 1 and 2 to the signal source from the spectrometer via the spectrometers fiber port. The collection efficiency was determined by comparing the amount of light exiting the probe (via the receiving fibers) to the amount of light entering the probe. The total light entering the probe was determined by coupling the common end directly to the power meter for each of the three probes under the same lighting conditions.
Table 7: Experimental results for the probes tested; here we see that the probe configuration dictates which leg of the probe is connected to the light source, and which one is connected to the detector. For example a “1-6” indicates the transmitting leg has 1 fiber and the receiving leg has 6 fibers.

<table>
<thead>
<tr>
<th>Experiment #</th>
<th>Probe Configuration*</th>
<th>NA</th>
<th>Core Diameter (μm)</th>
<th>Efficiency Ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6-1</td>
<td>0.53</td>
<td>600</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>6-1</td>
<td>0.37</td>
<td>600</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>1-6</td>
<td>0.53</td>
<td>600</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>20-20</td>
<td>0.2</td>
<td>200</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>1-6</td>
<td>0.37</td>
<td>600</td>
<td>5</td>
</tr>
</tbody>
</table>

*Second number indicates the number of fibers connected to the light source.
Figure 14: Experimental set-up to determine probe collection efficiency as a function of sample distance. The signal enters the transmitting leg of the probe via the fiber port, a). This signal is transmitted down the probe, b), and illuminates the sample, c), and is spherically reflected back up towards the receiving fibers in the common end of the probe. These receiving fibers guide the reflected signal into the optical power meter detector, d), and the light power is displayed on, e), the power meters console.
4.2.2 Experimental Results

Figure 15 i) and ii) respectively show results from the power-distance experiments for probes having the central fiber as the receiving fiber, and results from having the central fiber as the transmitting fiber. As expected, in both sets of results, there is an optimal distance at which we get the highest amount of returned power, followed by a rapidly decreasing amount of returned power as the probe is moved to greater distances from the sample. We can conclude from these experiments that by utilizing the central fiber as the transmitting fiber, and the surround fibers as the receiving fibers, that we obtain a much higher amount of returned signal. A maximum returned signal strength of approximately 10% was recorded; in comparison we recorded a maximum returned strength of approximately 1.4% for the configuration set up with the central fiber used as the receiving fiber. Optimal sample distance for the maximum returned signal strength configuration was around 2 mm and corresponds to fibers of NA 0.53.

Results indicate that the most efficient configuration is by utilizing the central fiber as the transmitting and using fibers with as high a NA as possible.
Figure 15: i) Shows the experimental results for probes with a central fiber as the receiving and the surrounding fibers as the transmitting. ii) Shows results from a configuration utilizing the central fiber as the transmit, surrounded by six receiving fibers. The first probe has a numerical aperture of 0.53 and the second probe has a numerical aperture of 0.37.
4.3 Probe Illumination Profile

The purpose of these experiments was to determine how light propagates once it leaves an optical fiber optic bundle and propagates towards the sample. An IR wavefront sensor was utilized for these experiments which allows a very accurate 3D profile to be recorded of the emerging light beams as they propagate from the ends of the optical fibers.

4.3.1 Experimental Set-Up

These experiments investigated the illumination profile of the common end of each of the probe configurations as a function of distance. They utilized a WinCamD (U-Series model http://www.dataray.com/) high resolution wavefront sensor (Figure 16 i); wavefront sensors are typically used to measure, to a very high degree of accuracy, the optical wavefront of an incoming beam, and is used extensively in the field of optics and lens testing.

One leg of the probe was coupled to the light source of the FT-IR spectrometer via the fiber port, whilst the common end of the probe was held directly above the WinCamD wavefront sensor Figure 16 i). Both the 2D and 3D illumination profiles were viewable via the software included with the sensor and these profiles are discussed in the next section. Due to the delicate nature of optical fibers it was necessary to inspect the fiber ends periodically via the optical fiber inspector instrument (Figure 16 ii) to ensure no major scratching of the fiber ends.
Figure 16: i) WinCamD wavefront sensor with experimental set-up illustrated above. A light source was coupled to leg-1 of the probe and illuminates the wavefront sensor. The illumination profile for various probe distances was recorded and then the experiment was repeated for the leg-2 of the probe. ii) An optical fiber inspector used to determine the condition of the end faces of the probes.
4.3.2 **Graphical Results: 3D-2D Profiles**

Figure 17 shows the results for the ‘6-1’ probe configuration, for the probe with 0.53 NA. Images a)-h) show a series of images at varying probe distances from the wave-front sensor. As expected, at a distance of 0 mm (i.e. probe in contact with the sensor), we got a very sharp, clean, crisp image in both the 2D and the 3D. As we move away three things occurred:

- The illumination profile spreads out.
- The radius of the illumination profile increased.
- The amount of noise in the illumination profile increased.

The cross hairs in the 2D profiles indicated the lines where the sensor outputs the raw data values of both position on the detector chip and the signal intensity; these values will be used in later sections to perform statistics on the illumination profiles.

Figure 18 shows the same basic detail as described above, except that in this experiment the central fiber was no longer transmitting the signal and illuminating the wave-front sensor, here the 6 receiving fibers were used as the transmit. At close proximity to the detector the 6 illumination profiles from each of the fibers showed up clearly. However, as we moved away, these signals combined and tended to “wash” each other out. By 2.5 mm, it was hard to see these contributions and we were left with a signal similar in physical appearance, to that of a single illumination profile.
Figure 17: Central transmitting fiber illumination profile, 3D and 2D. Images a-h show a progression of 3D and 2D images of the illumination profile as the probe moves away from the wavefront sensor. Probe distances from the sensor are shown in mm on each of the images.
Figure 18: Central receiving fiber surrounded by 6 transmitting fibers illumination profile 3D and 2D illumination profile. a-h show a progression of 3D and 2D images of the illumination profile as the probe is moved away from the wavefront the distance from the sensor is shown in mm on each of the images.
4.3.3 Graphical Results: 1D Profiles

The instantaneous 1D profile for the “1-6” and “6-1” configuration are shown in Figure 19 and Figure 20 respectively. In both sets of results, there is a significant amount of random noise which was reduced in the outputted datasets by using a time averaged value for intensity. This noise is a combination of imperfections in the fiber end (observed with the optical fiber inspector), dust in the atmosphere, background noise within the wavefront detector chip and fluctuations within the optical path inside the FT-IR spectrometer signal source.

4.3.4 Data Reduction and Analysis

The time averaged data values for the above 1D illumination profiles were outputted to a data file via the wavefront sensor software. For each 1D profile the standard deviations (Equation 5) of the entire set of intensity values were first calculated. Next, the normal curve was calculated for comparison to the actual intensity profile using Equation 6 with both sets of calculations being normalized to allow easy comparison. Equation 7 can be used to show a comparison between the 1D illumination profile and the normal curve for two distances, 0.5 mm and 3 mm. The significance of these derived standard deviations for all the results are summarized in the lower image of Figure 21 and will be discussed in more detail in the next chapter. As expected, the illumination profile follows a Gaussian distribution profile; here we see that the greater the probe distance from the sample, the more spread out the light, and the greater its standard deviation is. Figure 21 “a” and “b” show a comparison of the illumination profile overlaid with a Gaussian profile for distances of 0.5 and 3 mm. These results will be used to help develop and validate a numerical model (next chapter).
Figure 19 shows the 1D illumination profile for the “6-1” configuration (note that the scale changes between images). Here it can clearly be seen that at close distances we have a crisp, sharp profile, as the distance between the probe and the sensor increases, “noise” is introduced into the profile. Figure 20 shows the 1D profile for the probe in the “1-6” configuration, at close distances we can see the distinct contributions from the surrounding fibers. As the probe sensor distance increases, so does the dispersion of each of the illumination profiles; as we increase the distance the profiles begin to the point where it is not possible to differentiate each fibers individual contribution.

Equation 5: Standard Deviation

\[ \sigma = \sqrt{\frac{\sum(x - \bar{x})^2}{n}} \]

Equation 6: Probability Density Function

\[ f(x, \mu, \sigma^2) = \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{1}{2}(\frac{x-\mu}{\sigma})^2} \]

Equation 7: Normalization Equation

\[ Z = \frac{x - \mu}{\sigma} \]

Where: \( x \) = position on the x-axis, \( \mu \) = mean intensity value
Figure 19: Central transmitting fiber optic bundle 2D profile. These profiles were taken along the line running from the upper left to lower right in Figure 17. The y-axis is normalized and the x-axis has division scales indicated by the number on each image. The output data values are time averaged to remove reduce fluctuation in values.
Figure 20: Central transmitting fiber. Cross section of 2D profile. These profiles were taken along the line running from the upper left to lower right in Figure 18. The y-axis is normalized and the x-axis has division scales indicated by the number on each image. The output data values are time averaged to remove reduce fluctuation in values.
Figure 21: Comparison of the wavefront sensor illumination profile and the normal curve for distances i) 0.5 mm and ii) 3 mm.
4.4 Discussion

Results from the experimental investigations indicate that probes with the hexagonal “6 around 1” configuration gives the highest returned signal when the central fiber is used to transmit and the surrounding fibers are used to receive. Numerical aperture plays a critical role and this should be made as large as possible to allow the receiving fibers to be able to “see” as much of the reflected light as possible. These experimental results will be used to help develop the numerical model that is discussed in the next chapter. In this dissertation we will only be considering flat ended fibers, however by directly manipulating the fiber faces of it may be possible to improve upon the collection efficiency as illustrated below. Angling the fiber faces of the receiving fibers towards the central fibers illumination cone makes it possible to improve the collection efficiency.

Figure 22: Comparison between flat ended and angled fibers. Here we note that angled fibers can receive much more light at closer distances than flat fibers, meaning much stronger signal strength at close distances.
Here we review the fundamental geometrical mechanisms behind the results discussed in the previous chapter. Next we will develop a numerical model to predict probe efficiency that has been validated against our experimental results. There are an almost infinite number of different optical configurations; however this work will only deal with flat edged fibers that have no lenses or other light focusing optics added into the optical path.

### 5.1 Optical Field for an Individual Fiber

Light exiting a single illuminating fiber has a Gaussian intensity profile with the amount of surface illumination being a function of the distance from the center of the point directly beneath the center of the fiber. The intensity profile of the beam projected on a perpendicular planar surface is given by Equation 8.

Equation 8: **Gaussian Distribution Profile**

\[
I \propto \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{(r-\mu)^2}{2\sigma^2}}
\]

Where \( I = \text{local illumination } \text{W/m}^2 \)

\( r = \text{distance (m)} \)

\( \sigma = \text{standard deviation (m)} \)
In fiber optic technology, the diameter of the illumination field is described by the Numerical Aperture (NA). The value of NA is equal to \( \sin(\theta) \), where \( \theta \) is one-half the angle of the transmit or receive cone. Consider a simple transmitting fiber and a receiving fiber as shown in the below image. Consider that fiber “a” is transmitting a signal that produces the illumination cone that is labeled “b”. Fiber “c” has the same physical characteristics as the transmitting fiber, it also has a cone (“d”) but this cone is referred to as the receiving cone. The illumination cone cannot illuminate anything that does not fall within this cone, and the receiving fiber cannot collect light from anything other than what falls within its cone. A sample that lies within both the illumination cone and the receiving cone, “e”, will collect reflected light from the sample. The closer we move towards the transmitting fiber, the higher the light flux, but the smaller the amount of overlap between the receiving cone and the illumination cone.

Figure 23: Illustration of the illumination cone and the receiving cone of two side by side optic fibers. The illumination fiber, a), is transmitting a signal and creating an illumination cone, b), that overlaps the receiving fibers, c), receiving cone, d). This overlapping region is shown in e).
The diameter of its field of view on the sample located at a distance $L$ from the probe tip is then given by the following equation, and illustrated in the below figure.

Equation 9: Illumination Profile Spreading Function

$$d_{\text{field}} = (\text{diameter of fiber face}) + (\text{cone spreading on both sides})$$

$$= d_{\text{fiber}} + 2L\tan(\sin^{-1}(\text{NA}))$$

Where $d_{\text{fiber}} = \text{diameter of the illuminated or viewed circle under one fiber (m)}$

$d_{\text{field}} = \text{diameter of fiber at end (m)}$

$L = \text{probe to sample distance (m)}$

$\text{NA} = \text{fiber’s numerical aperture}$

The NA for an optical fiber is a function of its materials and dimensions and typically ranges from 0.22 to 0.53, resulting in light cone total angles of $2\theta = 25.4-64.0^\circ$. Since the beam profile is Gaussian there is no hard cutoff of the illumination as the definition of NA might imply. The NA actually describes the standard deviation of the distributed light. For modeling purposes the establishment of the standard deviation of the illumination profile was desired. Illumination profiles were measured via a wavefront sensor, using a beam profiler, at several probe distances, as discussed in the previous chapter. Next, a vertical slice was taken through each of the illumination profiles and analyzed to determine their standard deviations. Figure 25 shows a 3D image of the beam profile for the single, 600 $\mu$m fiber of $\text{NA} = 0.53$ at a distance of 1 mm from the detector. Image ii) shows intensity profiles for several probe distances, overlaid, as expected, as the probe distance is increased, the illumination profile spreads out. Image iii) shows a
comparison between the theoretical standard deviation of the illumination profiles distribution (using Equation 9) and the actual standard deviation. If the standard deviation is independent of the detector-probe distance, then the experimentally-determined values would form a straight line; however, at close distances, stray light from the cladding spreads the beam significantly. The solid line results from the values we use in our modeling by setting the light cone radius, as given by the definition of NA, to $3\sigma$. This agrees well with the measured values outside of the close-in scatter zone and includes 97.1% of the total light within this area.

Figure 24: Illustration of the geometry of an optical fibers transmittance or receiving cone. Where $L$ is the probe-sample distance and $\theta$ is a function of the numerical aperture of the fiber.
Figure 25: i) 3D beam profile obtained via a wavefront sensor at 1 mm distance. ii) Intensity profile at several probe-sample distances. iii) Comparison of estimated $\sigma$ from beam image profile and theoretical $\sigma$ defined via the numerical aperture. Here is a larger than expected $\sigma$ at close distances due to the stray light emitted via the cladding.
5.2 Light Interaction

The Bi-directional Reflectance Distribution Function (BRDF) describes how light interacts with surfaces and is a function of the angle of incidence, light absorbed, light reflected and transmitted from the surface. In this simplified model the surface is assumed to have an albedo of one so all the illumination received by an element will be retransmitted. Surface reflection is considered to be diffuse so the emission pattern from each surface element is modeled as a symmetrical hemisphere. The amount of light returned to the FTIR through the receiving fiber is equal to the sum of light from each surface element that falls on the face of the receiving fiber. In a fashion similar to the illuminated circle, the face of the receiving fiber is divided into square finite elements, each 1/100 the diameter of the fiber. Our ray tracing program steps through each surface element in the illuminated circle and performs the following calculations:

1. Is this surface element visible to the receiving fiber? This is accomplished by using the receiving fiber's NA and distance to the surface to calculate the circular area it can see.

2. If the surface element can be seen by the receiving fiber, the intensity of illumination from this one surface element is calculated for every element on the face of the receiving fiber. For each fiber element, the flux reaching it from that one surface element is calculated from the inverse square law using the distance between the two elements. This flux is multiplied by the area of the fiber element and then corrected for the angle of incidence between the surface element and the fiber element by multiplying by the cosine of the angle of this ray to the fiber face. The sum over every fiber element is the total amount of light entering the fiber from that one surface element.
3. Step 2 is repeated for each visible surface element and the total amount of light into the fiber is summed up. For this algorithm, the maximum number of element to-element calculations would be $7854^2$ or approximately 62 million. It is less than this if the entire illumination circle is not seen by the receiving fiber, which is normally the case.

5.3 **Pseudo Code**

The below pseudo code describes how the numerical model was created in MatLab. The code pulled in all the initial variables, such as probe-sample start and end distance, NA of fibers, fiber radius etc. from an Excel spreadsheet. The calculations performed in each of the steps below were stored into an array. The below figure was used in conjunction with the below pseudo code to develop the model. This work, “Numerical Modeling and Optimization of a Bundled Fiber Optic FTIR Probes for Spectroscopy of Small Targets”, published in Advances in Space Research (R.P & R.K, 2011) and was presented at the Lunar and Planetary Science Conference (LPSC) poster session (*In situ* Instrumentation) (RP Pilgrim & Ulrich, 2011). Figure 26 shows the sample grid and the receiving fibers surface area are both divided into high resolution grids. In this illustration Fiber 1 illuminates the sample grid with a Gaussian distribution profile, the total light at each grid point is then reflected back up away from the sample grid in a spherical wave fashion.
Figure 26: Illustration of two optical fibers. The sample area was split up into a high resolution grid. Fiber-1 is transmitting; fiber-2 is receiving the reflected light. “1” is the illuminated area, “2” is the receiving fibers possible receiving area and “3” is the actual light from fiber-1 that can be detected by fiber-2. The receiving fiber surface active area is also split up into a grid (“4”).
**Numerical Model Pseudo Code**

The Compete MatLab listing is in the appendix (Numerical Model Core MatLab Code)

FOR EACH sample distance DO

(A) %Flag Transmitting and receiving points on sample surface grid
FOR EACH grid point on sample grid DO
    IF current grid point falls within illumination area THEN DO
        Illumination area flag=TRUE
        %Using a Gaussian distribution profile
        Calculate power arriving at grid point
    NEXT

(B) FOR EACH point on sample grid DO
    IF current grid point falls within receiving fibers area THEN
        Receiving area flag=TRUE
    NEXT

(C) FOR EACH point on sample grid DO
    If illumination flag AND receiving flag=TRUE THEN
        Overlap flag=TRUE
    NEXT

(D) FOR EACH point on grid WHERE overlap flag =TRUE DO
    FOR EACH point on receiving area grid DO
        Calculate distance from receiving grid point to current sample grid point
        %Assume a spherical reflection from the sample grid
        %Using the power calculated in (A)
        Calculate flux from sample grid point arriving at receiving area grid
    NEXT

NEXT

NEXT
5.3.1 Example Case

This algorithm will be demonstrated using the simplest possible case of two identical fibers mounted side-by-side resulting in an illuminated zone and a receiving zone corresponding to the field of view of each fiber. It is only where these two circular zones overlap that light reflects off of a sample and is transmitted back up into the receiving fiber (Figure 23 e). Each fiber had a total diameter of 660 μm of which 600 μm was the fiber core and capable of light transmission, the remainder being cladding as described above. Each had a numerical aperture of 0.40 giving a light cone total angle of 47.2°. Figure 27i), shows the percent of incident light from one illuminating fiber that is returned through a single adjacent receive fiber for the fibers described above. The received power is zero at a distance of 0.5 mm from the surface because the two light cones do not overlap at distances closer than this. As the fibers are pulled away from the surface there are two competing effects: increasing overlap of the light cones and decreasing illumination flux returning to the receive fiber due to the inverse square effect. The result is a peak return of about 1.7% at a distance of 2.5 mm when the diameter of both light cones at the surface are each 2.7 mm in diameter. The albedo of any real surface will be less than one and the results shown in this figure can simply be scaled by the actual albedo value so, for a sample that has the average albedo of the Moon (13%) the return would be about 0.22% of the light sent from the FT-IR unit. The FT-IR unit can compensate for low return levels by integrating the signal for a longer time as long as the returned light level is above the noise level of the system. Low return fractions could become a problem if there is stray light from nearly non-planar surfaces that fall on the face of the receiving fibers but, when analyzing small sample areas, the fiber ends tend to be very close to the sample and will shade themselves to some extent from stray light. Figure 27ii), shows the size of the sampled area on the substrate. For any fiber
configuration and number the sampled area is any area that is both illuminated by any fiber(s) and seen by any receive fiber(s). For this example case of two fibers side-by-side, that area is the intersection of two circles. When the fibers are close to the surface this amounts to a spindle-shaped area and, as the fibers are withdrawn. The overlap becomes closer to a pure circle. Because the sampled area is the intersection of two light cones on the surface, the sampled area can be considerably less than the fiber face area. On Figure 27ii) the area decreases to zero at 1 mm distance because of the non-transmissive cladding that makes up the outer 10% of the fiber's diameters. The diameter at maximum light return is about 1.8 mm. These distances are the same order of magnitude as the hematite "blueberries" and the thin layers seen by the MER spacecraft on the surface of Mars.

5.4 Model Validation

As discussed in the previous chapter, two 1.5 m long probes were custom built, consisting of seven Optran Ultra glass silica fibers with core diameters of 600 μm, and a total diameter of 660 μm. Experiments were designed to validate our numerical model using the two different probes. The first probe had fibers of NA = 0.53, while the second probe had fibers of NA = 0.37; both probes had the hexagonal configurations. Figure 28 shows a comparison of the probe collection efficiency as function of sample distance, together with the predictions from the ray tracing model for two different probes.
Figure 27: i) The percent of incident light returned to the FTIR unit as a function of probe distance from the sample. This case is a single transmit fiber next to a single receiving fiber both with a diameter of 0.66 mm and a numerical aperture of 0.4. ii) The diameter of the sampled area. The shape of this area depends on the probe configuration and, for this simplest case of two adjacent fibers, it is spindle-shaped but becomes more symmetrical with the use of more fibers or as the sample to probe distance increases. To provide an easier comparative value we express the sample size as the diameter of a circle with the same area as the sampled.
The model tends to diverge slightly from the experimental results as we move away from peak performance distance, due to the simplifications in the numerical model. The BRDF is adequate for identifying the underlying trends discussed in the next section. The broader $\sigma$ than predicted at close distances (Figure 25) is the result of stray light emerging from the cladding. The purpose of the cladding is to provide the change in refractive index at the boundary which is needed for total internal reflection to occur within the core. Light that does not undergo total internal reflection in the core enters the cladding leading to a small amount of light emerging from the cladding at the probe tip. This light scattering at close distances, coupled with the cross talk of the fibers, is responsible the higher than expected returned signal strength at very close distances.

Figure 28: Comparison of numerical model and experimental results for two probes with core diameters of 600 μm. Probe 1 has fibers of NA=0.53, probe 2 has fibers of NA=0.37. Deviation at very close distances for both probes is caused by stray light emerging from the cladding.
Figure 29: i) Fractional light return for a six-around-one (central fiber transmitting) configuration with transmitting fiber NA values of 0.2 to 0.5 and receiving fiber’s NA held constant at its largest value of 0.5. ii) Same FOB as modeled in i) but here we make the central fiber the receiving fiber and the surrounding fibers as the transmitting. Here we see a clear advantage using the central fiber as the transmitting fiber. As we decrease the NA of the transmitting fiber(s) we decrease the overall probe collection efficiency.
5.5 Probe Design and Performance

The model was used to calculate the light returned and the size of the sampled area as a function of probe distance for a six-around-one configuration of 660 μm fibers. As discussed in the previous chapter, as the total number of fibers in a probe is decreased with the same total probe face area (using fewer but larger fibers in the same space), the active area increases slightly. Seven of these fit well into a standard SMA905 fiber optic connector. The model was run for both six receive around one transmit and six transmit around one receive. The NA of the transmitting fiber varies from 0.2 to 0.5 while the receiving fiber's NA was held constant at 0.5 since it is always more efficient to use receiving fibers with the largest possible viewing area. Figure 29 shows the results for the percent of total incident light returned to the instrument. In all cases the total amount of light entering the system has been kept at the same value regardless of the number of transmitting fibers, to allow for convenient comparison across the various configurations. By placing the transmitting fiber in the center and surrounding this fiber with receiving fibers, much higher return signal strength is achieved compared to having the central fiber being the lone receiver. Larger values of transmit NA provided better light return for the smaller probe-to-surface distances, but smaller NA's perform better for larger distances. The highest return is for the central transmit configuration with the largest transmit NA at a distance of around 2 mm.

Based on the results above and the experimental results, the six-around-one configuration with the central fiber transmitting is optimal based on the active area of the bundle end and the light gathering ability of the assembly for probes that can be made using commonly available fiber size. We now turn to the size of the area sampled by this technique. Figure 30 shows a series of
scale drawings illustrating the overlap between transmit and receive light cones on the sample surface as a function of distance of the probe tip from the surface. The central transmit fiber has a small NA of 0.2, and the receive fibers have large values at 0.5. When the fibers are in contact, there can be no overlap, and the diameter of each of the seven areas is simply the fiber diameter, 600 μm. As the probe is withdrawn, all seven areas expand according to Equation 9.

Diameter of illuminated region in center (mm) =

\[ 0.60 + 0.41 \text{(distance to surface (mm))}, \text{ for NA} \]

= 0.2 diameter of each of the six sensed regions (mm)

= 0.60 + 1.15 \text{(distance to surface (mm))}, \text{ for NA}

=0.5

Comparing the bottom curve from the left side of Figure 28 and Figure 29 shows that the percent of light return increases as the receive areas increase their overlap with the illuminated circle, and once that overlap is complete, the inverse square law comes into play to decrease the light return. Once any degree of overlap begins to occur, at less than 0.2 mm distance, the diameter of the sampled area is the diameter of the illuminated circle.

The left side of Figure 31 is a sub-plot of the left side of Figure 29, and the right side is the diameter of the sampled area. Both sides are at the same scale of distance from the substrate. The sampled diameter is essentially the diameter of the illuminated circle once overlap starts to occur; the lines begin when this overlap starts. Even though the center of the illuminated circle is not illuminated at the start of overlap, the ring represents the size of the area that is both illuminated and seen, so it is the diameter that is sampled.
Figure 30: Illuminated area (center) and receiving areas for the six fibers surrounding the central transmitting fiber. Central fiber has a NA = 0.2, receive fibers have NA = 0.5. As the probe-sample distance increases from 0 mm to 0.7 mm we see the amount of overlap between the transmitting area and the receiving area increase. In this particular example complete overlap is at 0.7 mm.
Figure 31: Light received and sample size diameters as a function of probe distance for a six-around-one configuration with transmitting fiber NA values of 0.2 to 0.5, and the receiving fiber NA holds constant at its largest value of 0.5.
5.6 Discussion and Conclusion

Results indicate that when a small working distance is needed for characterizing small areas, it is optimal to use transmitting fibers with a high numerical aperture as these will give a higher return signal strength; however, this signal quickly decreases with increases in working distance. If the working distance is much higher, then a smaller transmitting numerical aperture will be more efficient at providing much higher returned signal strength. The most optimal design model has a signal collection efficiency of around 9% at a probe-sample distance of 2 mm with a spot size of about 3 mm in diameter. This decreases to just below 1% at around 15 mm from the sample producing a spot size of around 18 mm in diameter. While the models do start to diverge from the experimental results once moved to larger distances, the trend is clear; the distance between the tip of the fibers and the sample plays a critical role in determining the returned signal strength. The experimental results and models focus on a sample with an albedo of 1, however, in reality; samples will have a much lower albedo. For example, the surface of Mars has a typical albedo of around 0.15 so even if 100% of the reflected surface signal is collected it would still have decreased by 85% from the origin signal; so optimizing the collection efficiency is a crucial aspect of probe design.

This numerical modeling was used to form the basis for the optical design of very small, highly optimized fiber probes for optical spectroscopy, for applications requiring precise knowledge about the field of view and optical response as a function of sample distance. These models highlight the two main parameters to take into account when designing a fiber optic probe. When designing probes that have additional optics coupled to the fiber tip, such as prisms and windows increase the working distance and should be taken into account when optimizing fiber bundles.
In conclusion, space applications typically require low power, mass and volume, and we have demonstrated here that it is possible to significantly increase the returned signal strength from a fiber optic probe without the need to increase the incoming signal strength or detector sensitivity, which may have added additional power requirements or mass. Optimizing fiber array configurations and fiber selection represents the easiest way to increase the return signal strength, and knowledge of the expected working environment will allow the most efficient probes to be designed. This work models flat end faced fibers, but further optimization is possible by polishing the fibers at an angle to produce end faces that focus the transmit/receiving areas onto the sample, thus increasing illumination flux. This continues to be a topic for further modeling, given the need for powerful and lightweight remote sensing equipment on future planetary landers and rovers.
CHAPTER 6 SPECTRAL VALIDATION

To satisfy the requirements of TRL 3, a small selection of spectra were taken over the transmission range of the FOB. These spectra were then compared against standard reflectance spectra to demonstrate accuracy and repeatability. We also attempted to create and analyze “icy regolith” with limited results. Finally, we integrated FOB’s into other research areas of other research group such as the Titan simulation chamber, which demonstrates the probes use under a more “mission like environment”

6.1 JSC Mars-1

In order for us to test and develop equipment and instrumentation here on Earth for missions to Mars it is necessary to replicate the expected Martian conditions as closely as possible. There are many types of Martian regolith analogue material, and the choices on which to use will depend upon what type of instrumentation or equipment are being developed. For this chapter we evaluate the probes ability to perform spectroscopic analysis; therefore, we will utilize the best spectroscopic analogue for Mars, which is the Johnson Space Center Martian simulant (JSC Mars-1). Other types of analogues include chemical, mechanical (discussed in chapter 7), physical, organic and magnetic, detailed in Table 8 (Marlow, Martins, & Sephton, 2008)
Table 8: Martian analogue types and descriptions. The choice of analogue is dependent upon the properties under investigation. JSC Mars 1 is the best spectroscopic analogue (table adapted from (Marlow et al., 2008)).

<table>
<thead>
<tr>
<th>Analogue Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical/ Spectral</td>
<td>Spectrum</td>
</tr>
<tr>
<td></td>
<td>Dielectric constant</td>
</tr>
<tr>
<td></td>
<td>Redox potential, pH</td>
</tr>
<tr>
<td></td>
<td>Electrical conductivity</td>
</tr>
<tr>
<td></td>
<td>Volatiles, Mineralogical composition</td>
</tr>
<tr>
<td>Mechanical/ Physical:</td>
<td>Cohesive strength</td>
</tr>
<tr>
<td></td>
<td>Angle of internal friction</td>
</tr>
<tr>
<td></td>
<td>Particle size, shape</td>
</tr>
<tr>
<td></td>
<td>Density, Bulk density. Porosity</td>
</tr>
<tr>
<td></td>
<td>Water content</td>
</tr>
<tr>
<td></td>
<td>Albedo, Thermal inertia</td>
</tr>
<tr>
<td></td>
<td>Morphology Depth of layer</td>
</tr>
<tr>
<td>Magnetic</td>
<td>Magnetic susceptibility</td>
</tr>
<tr>
<td></td>
<td>Saturation magnetization</td>
</tr>
<tr>
<td>Organic</td>
<td>Total organic carbon</td>
</tr>
<tr>
<td></td>
<td>Molecular abundances</td>
</tr>
<tr>
<td></td>
<td>Culturable counts</td>
</tr>
</tbody>
</table>
JSC Mars-1 was developed by NASA and made available in large quantities in 1997. JSC Mars-1 represents one of the best spectroscopic analogues for the Martian regolith. JSC Mars-1 consists of weathered volcanic ashes, mined from a cinder cone located in Hawaii, we purchased a small quantity for this research project.

6.2 Preliminary Spectra

In addition to JSC Mars-1, other elements were analyzed to help aid in the interpretation of the any returned spectra from the OPRA probe. The goal of this work is not to develop an extensive spectral library, but to demonstrate that spectra obtained with the FOB are accurate. By obtaining spectra with the probe and then cross referencing those spectra with spectra of the same minerals taken with the standard reflectance sample bay of the FTIR, we can confirm that we are actually able to take usable spectra with the probe. This is why every new space bound spectrometer, such as the Thermal Emission Spectrometer (TES) on board the Mars Global Surveyor (MGS) have a spectral library compiled from spectra taken with the instrument (Philip R. Christensen et al., 2000). The list of elements used for spectral comparison is shown below. Here we see that the key spectral features are clear and consistent across both the standard reflectance and the FOB spectra. This selection of spectra is by no means meant to be a complete spectral library of all the anticipated minerals, but it does demonstrate that the FOB is able to clearly differentiate between various spectral features.
- calcium chloride (anhydrous)
- calcium chloride (dihydrate)
- calcium sulfate (anhydrous)
- calcium sulfate (dihydrate)
- ferric oxide red
- olivine
- iron metal
- iron(iii) hydroxide
- jsc mars-1
- kaolinite
- magnesium sulfate
- montmorillonite
- nontronite
Figure 32: Spectra of calcium chloride (Anhydrous), kaolinte, calcium chloride (ehydrate) and anhydrous calcium sulfate. Axes are offset for clarity. Spectral comparison of several different elements. Solid black line are spectra obtained via a FOB, dotted lines are obtained via standard reflectance using the sample bay of the FT-IR.
Figure 33: Spectra of calcium sulfate, nontronite, montmorillonite and olivine. Axes are offset for clarity. Spectral comparison of several different elements. Solid black line are spectra obtained via a FOB, dotted lines are obtained via standard reflectance using the sample bay of the FT-IR.
Figure 34: Spectra of metallic iron, ferric oxide, magnesium sulfate and iron hydroxide. Axes are offset for clarity. Spectral comparison of several different elements. Solid black line are spectra obtained via a FOB, dotted lines are obtained via standard reflectance using the sample bay of the FT-IR.
6.3 Icy Regolith

As discussed in chapter 1, one of the main goals in planetary exploration is to identify indigenous resources that we may be able to utilize in support of manned missions. We know that water ice is very abundant beneath the Martian surface as indicated by results from the Mars Odyssey orbiter. Numerical models (Ulrich et al., 2010) indicate the strong possibility of icy regolith beneath the surface and results from the gamma ray spectrometer instrument (Figure 35i) further support the possibility for near subsurface ice. The most recent direct evidence for near subsurface ice has been provided by the Phoenix mission utilizing a scooping instrument to remove the top layer of regolith, to reveal solid ice Figure 35 ii) and iii). Until we are able to successfully perform a sample return mission to Mars, we have to use Martian regolith analogues. JSC Mars-1 regolith analog is spectroscopically a very close match for what we find on the surface of Mars and is used in this section to try and produce an “icy regolith” sample. This will then be used to demonstrate that FOB can differentiate between frozen regolith samples with various degrees of water content.

There are three main ways in which “icy regolith” and permafrost may form on planetary bodies. These are determined by where the water originally came from before it was frozen, Figure 36. Condensing water from the atmosphere onto the surface may lead to vapor diffusion from the surface, down into the regolith where it may be frozen. Surface water may lead to either gravity transfer to deeper depths within the regolith where it may freeze, or may lead to vapor diffusion. The third method is a sub-surface water source which may lead to water transport into colder regions via thermal gradients or pressure gradients or may lead to in place freezing if the temperature drops to a low enough temperate. Figure 36 was adapted from Mackay, 1972. Here
they give a full review of the field of underground and how these theories may be used to help explain various features we see on other planets as a direct result of these underground ice formation processes.

Figure 35: i) Mars Odyssey gamma ray spectrometer map indicating likely water ice below the subsurface. ii) Ice revealed underneath the Phoenix Lander. iii) Ice exposed via the scoop on the Phoenix mission.
Figure 36: Ground ice formation processes, we were able to reproduce in place freezing within JSC Mars-1 regolith in the laboratory (image adapted from Mackay, 1972).
6.3.1 Method

While our research labs lack the facilities to reproduce these ice formation methods for all but the simplest of cases (in place freezing), we were able to get some preliminary results.

Numerous attempts were made before finalizing on this method to produce icy regolith with various amounts of water content. Step 1 involved determining the water saturation limit of our JSC Mars-1 regolith. A sample was under vacuum baked overnight at a 160-180°C as shown in Figure 37i) to ensure all water content was removed. The regolith was then weighed ii) to determine its “dry” mass, and then was left to soak in water overnight to fully saturate the regolith with water.

Figure 37: i) The oven is used to bake the samples to remove all water. The regolith is then weighed to determine its “dry” weight, ii). Then the regolith was soaked in water overnight to saturate the regolith. Once saturated, excess water was removed via a centrifuge, iii), and the
remaining saturated regolith is weighed again to determine how much water was taken into the regolith.

Once fully saturated, samples were placed into a centrifuge (iii) to separate any excess water and then the regolith is drained, and again weighed. This density is used to define the 100% saturation limit of the regolith; the baked sample density is defined as a saturation of 0%. Several samples are prepared with various weight percent as shown in Table 9.

6.3.2 Results

Icy regolith manifests itself in the spectra by altering the band depths, most notably around the 1.5 and 1.9 micron region of the standard dry JSC Mars-1 regolith. Whilst this is by no means an in-depth analysis into the correlation between water content and spectral alterations, clearly the FOB’s are sensitive and accurate enough to detect these changes in spectra.

6.4 Andromeda Chamber Upgrades

The Andromeda chamber is a key piece of equipment within the Space Center and is primarily used to run experiments under Martian-like pressures and temperatures. It is a cylindrical low-pressure chamber measuring approximately 61 cm in diameter and 208 cm in height (Sears & Chittenden, 2005), which can be custom fitted with various experimental modules which are tailor designed and made for a particular set of conditions you want to replicate in the chamber. This chamber represented an ideal opportunity to use a FOB probe within a more realistic
working environment, and to demonstrate that they still function in a low pressure low temperature environment. The hardware integration was designed with the view of allowing not only spectra to be obtained via a probe, but also allow devices such as web-cams, digital microscopes and LED lights to work alongside the probe. These upgrades were decided after several meetings with key people within the Space Center and was facilitated by building a custom vacuum feed through that allowed USB cables, FOB and additional power cables to run within the chamber. These upgrades prove conclusively that FOB’s can function effectively within hostile environment. Numerous papers have been made possible by this equipment, and it further validates the spectra taken with the FOB. The upgrades and FOB have worked without failure since early 2009.

Table 9: Various samples used to create the icy-regolith spectra.

<table>
<thead>
<tr>
<th>%</th>
<th>Dry Sample Size (g)</th>
<th>Added Water (g)</th>
<th>Total Sample Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>8.00</td>
<td>0</td>
<td>8.00</td>
</tr>
<tr>
<td>20</td>
<td>8.00</td>
<td>1.07</td>
<td>9.07</td>
</tr>
<tr>
<td>40</td>
<td>8.00</td>
<td>2.14</td>
<td>10.14</td>
</tr>
<tr>
<td>60</td>
<td>8.00</td>
<td>3.21</td>
<td>11.21</td>
</tr>
<tr>
<td>80</td>
<td>8.00</td>
<td>4.28</td>
<td>12.28</td>
</tr>
<tr>
<td>100</td>
<td>8.00</td>
<td>5.35</td>
<td>13.35</td>
</tr>
</tbody>
</table>
Figure 38: Andromeda chamber side view, i), top view, ii) and internal view, iii). Before the additional installations and upgrades.
Figure 39: Comparison of spectra from regolith’s with different weight percent of water. Here we can see definite changes in spectra as we increase the amount of water in the sample.
6.4.1 Designing and Building the Custom Vacuum Feed Through

Enabling multiple power cables, USB cables and a FOB to enter a chamber under pressure and maintain a perfect seal, took several iterations over a 2 week period; only the final approach is discussed here. Allowing the USB cables to enter a pressurized chamber while maintaining a seal proved very problematic. USB cables contain several sub cables twisted together and surrounded by a wire sheath to reduce electrical interference and plastic jacket. It was necessary to completely sever the USB cables and strip the internal wires bare. Then, each bare wire was soldered back to the appropriate cable (which is stripped to remove any outgassing and leakage). The sheath was also reconnected but soldering was not necessary as the sheath acts as an interference shield and does not carry any signal. Next, each of the reattached cables are placed into a pre-molded epoxy container that was made to fit inside the flange (Figure 41 d-ii)). The epoxy was left to bond and dry with the flange for a 24 hour period and then tested for leaks under a negative pressure in a small chamber. Once tested it was attached to the Andromeda chamber.

The optical fibers were coupled via a standard flanged which is drilled in the center and incorporated a female to female SMA-905 connecter. By integrating this connector, it was not necessary to run a single FOB through the lid of the chamber; instead, we could connect a separate fiber to the inside of the chamber lid and a separate fiber to the outside. The final fully tested flange is shown in Figure 40a), here we see i) the power cables and USB feed through. The epoxy is sanded down to remove any excess; ii) shows the optical feed through, iii) shows part of the 10 m long FOB wrapped around the chamber lid. Figure 40b) shows a simplified illustration of how the probe connects to the chamber. The total length of fiber needed was 10 m
to reach the chamber, and 3 m patch cable within the chamber which is shown here as a straight cable. In reality, this 3 m fiber was coiled once (with a diameter equal to that of the inside dimension of the chamber) to allow for the lowering of the experimental bay within the chamber. This allowed for a much more flexible setup with regard to the positioning of the FOB within the chamber and the storage of the probe when not in use within the chamber. The initial experiment performed within the chamber is shown in Figure 41. Image i) shows a top down view of a small, purpose purchased optical breadboard with several post and clamps securing the instrumentation shown; here the LED light source, webcam and FOB mounted directly above a balance (digital microscope is not shown). Image ii) shows the same experiment, but from a different point of view, iii) shows an image taken of a JSC Mars-1 simulant sample within the chamber.
Figure 40: i) Andromeda chamber after upgrades, here we see part of the 10 meter long FOB probe wrapped around some attachments on the lid. Attached is an addition custom made flanges which allow additional hardware to be integrated into chamber A) are additional USB ports, B) is where the FOB probe is connected. ii) Shows an illustration of how FT-IR is connected into the chamber.
Figure 41: i) Small optical breadboard set up with a balance. LED light source, webcam and FOB probe. ii) Side view of first image, sample is be placed directly below probe. iii) JSC Mars-1 and probe shown from inside chamber. iv) Smaller chamber used to test the experimental configuration and to check for leaks in the chamber feed through that was made.
6.5 Environmental Testing of the FOB

Testing a fully manufactured probe under a “space-like” environment was not inside the scope of this research, and not needed for a TRL of 3; however, the FOB discussed in the previous section was fully integrated into a research groups “Titan simulation” module which was utilized within the Andromeda chamber and led to this research group publishing several papers and abstracts (Research and development of this module was led by Wasiak et al, images used with permission from Wasiak). The Titan module was designed to allow reproduction of a Titan like environment within the Andromeda chambers (90K and pressures as low as 1.5 bar (F. C. Wasiak et al., 2012)). Figure 42 i) shows the top of the Andromeda chamber, with a probe attached, ii) shows the Titan module, iii) shows the accumulation of the acetylene slurry and iv) shows a side view with the liquid nitrogen bottle in the image.

Figure 43 shows spectra of liquid methane and acetylene ice obtained and used with permission from the Titan research group (F. Wasiak et al., 2011) like conditions, both the spectra of acetylene ice (taken at -119 C (154 K), 1 bar) and liquid methane (-180 C (93 K), 1.5 bar) were obtained by the FOB, installed as part of the FOB environmental testing.
Figure 42: i) Top view of Andromeda chamber. Here the probe is entering the chamber via the custom made feed through. ii) Titan simulation module that fits inside the chamber (developed by Wasiak et.al). iii), Actual image obtained from with a Titan experiment. Here we see Acetylene ice (image Wasiak et.al). iv) Side view of chamber.
Figure 43: Demonstration of optical bundle under more space like conditions. Spectra of i) Acetylene ice and ii) Liquid methane taken by the Titan research team (Wasiak et al.). Taken within the Andromeda chamber.
6.6 Testing FOB’s in the Lab

To date there have been at least 15 publications either in journals, conference proceedings or posters that would not have been possible without the use of the FOB’s developed during this research project, and several more publications and posters are currently being written. A complete list of works utilizing FOB can be found in Appendix 1.3.

6.7 Discussion

By integrating FOB’s within several other research groups it has been possible to validate that FOB’s can be a valuable and versatile piece of equipment. We obtained standard reflectance spectra of the JSC Mars-1 simulant using the standard sample bay of our Nicolet FT-IR spectrometer, and with the FOB, as well as several other elements. We attempted to simulate “icy regolith” with a limited degree of success. Although, we clearly identify that FOB’s are able to detect changes in the spectra due to varying degrees of water content. Whilst not a requirement for a TRL 3, FOB’s were integrated into several other research areas within the Space Center, most notably the Titan research groups experiments which allowed the center to produce previously unattainable results and publications. Here it was demonstrated that even under Titan like conditions, FOB’s function without issue.
CHAPTER 7 PROBE HOUSING

DESIGN AND STRUCTURAL ANALYSIS

The probe housing provides not only structural support but also serves as a barrier between the optical fibers and the harsh space environment. The purpose of the work reported in this chapter was to ensure that the structure could survive the anticipated mechanical stresses and strains of being pushed into the regolith. The force required to penetrate the subsurface is a function of the mechanical properties of the regolith and the size of the probe. Here penetrometer data obtained from the Apollo missions on the lunar surface will be reviewed. Data obtained via the Mars Viking and Pathfinder missions are also reviewed to help estimate the anticipated mechanical properties of the Martian regolith along with experiments into Martian regolith mechanical simulants.

These mechanical properties are used to determine an upper limit on the expected forces needed to penetrate into the subsurface. Structural analysis of the probe housing is then performed via Finite Element Analysis (FEA) under the anticipated loads to ensure structural integrity is maintained throughout the penetration processes.
7.1 Estimating Penetration Forces

7.1.1 Cone Penetration Testing

Cone Penetration Testing (CPT) is a nondestructive technique used to investigate subsurface characteristics. First used in the early 1900’s, CPT is based on the principle of measuring the force required to push a standardized penetrometer (36 mm diameter with a 60 degree cone tip) through the material in question, and comparing the force profile to known standards calibrated with the same standardized penetrometer. The mechanical properties of the regolith such as grain size distribution, bulk densities etc. will determine the necessary amount of force needed.

7.1.2 Mechanical Properties of the Martian Regolith

Results from the Viking mission indicate that the Martian regolith has a bulk density of 1.2 ± 0.2 and 1.6 ± 0.4 g cm\(^{-3}\) for loose and blocky material respectively with a loose regolith porosity of 60% ± 15% (Clark et al., 1977). Independently the Mars Pathfinder mission gave a bulk density of 1.52 g cm\(^{-3}\) (J. R. Matijevic, J. Crisp, D. B. Bickler, R. S. Banes, B. K. Cooper, 1997). The standard Martial regolith simulant is the JSC Mars, which is a very closely matched spectroscopic analogue; however, mechanically it is not the best analogue to use. JSC Mars-1 has a particle density, loose bulk density and bulk density after vibration of 1.91, 0.87 and 1.07 g cm\(^{-3}\), respectfully which correlates to a porosity of around 54% for loose and 44% for vibrationally-packed regolith. A comparison of the Viking and Pathfinder missions with the JSC Mars-1 regolith simulant, shown in Table 10, indicates a significant difference between the density and porosity which highly affects the results of any mechanical experimentation such as penetration experiments.
A more suitable simulant was developed (Seiferlin et al., 2008) as a mechanical analogue for the Martian regolith and was named the UK4 simulant. Penetration experiments are conducted into the UK4 simulant using a slightly smaller tip penetrometer (18 mm in diameter) than the standard terrestrial CP test. As expected, results indicate that bulk density plays a critical component in determining the force needed to penetrate into the subsurface. Figure 44 (adapted from Seiferlin et al., 2008) shows the total force needed to penetrate to a depth of just over 20 cm with UK4 (extrapolated to 50 cm) for bulk densities of 1.35, 1.45 and 1.55 g.cm$^{-3}$.

“The definition of a soil simulant does not require it to mimic many or all properties of the simulated soil. This constraint is probably difficult or impossible to overcome, and must be taken into account. If the property to be studied by a specific series of simulation experiments is not representative in a soil simulant ‘‘X’’, then ‘‘X’’ is not a fit soil simulant for the envisaged purpose.” ....(Seiferlin et al., 2008)

The total force experienced by a penetrometer is a function of 1) cone resistance ($q_c$), which is proportional the cross-sectional surface area of the probe and 2) sleeve friction ($f_s$), which is proportional to the total surface area of the sleeve of the probe beneath the subsurface. By analyzing the friction ratio $R_f=f_s/q_c$ for a wide range of soil types it has been possible to build arrays of soil classification charts to help interpret CPT measurements (Tom Lunne, Peter Kay Robertson, John J. M. Powell, 1997). One of the observations in building these charts is that $R_f$ is low in dry, sandy like materials, similar to what we find on Mars, meaning that $f_s$ is relatively low so we may, for order of magnitude estimates consider the penetration force a direct function to the diameter of the probe. The experimental results shown in Figure 44 were also verified by the same research group via a finite element analysis model used to determine the stress of a
penetrometer entering the UK4 simulant (Zöhrer & Kargl, 2006). These results indicate that to penetrate to a depth of 50 cm in the material with the highest bulk density used by the group (1.55 g cm$^{-3}$) requires a stress of approximately 5,305 N.m$^{-2}$.

Table 10: Martian regolith and Martian simulant properties. Here we note that the UK4 simulant is a much closer mechanical analogue than the JSC Mars-1 simulant to the Martian Regolith.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Viking 1 landing site, wind drift</td>
<td>1.2 ± 0.2 g.cm$^{-3}$</td>
</tr>
<tr>
<td>Viking 1 landing site, blocky soil</td>
<td>1.6 ± 0.4 g.cm$^{-3}$</td>
</tr>
<tr>
<td>Viking porosity</td>
<td>60% ± 15%</td>
</tr>
<tr>
<td>Pathfinder landing site</td>
<td>1.52 g.cm$^{-3}$</td>
</tr>
<tr>
<td>JSC (Mars-1) particle density</td>
<td>1.91 g.cm$^{-3}$ (± 0.02 g.cm$^{-3}$)</td>
</tr>
<tr>
<td>JSC (Mars-1) loose</td>
<td>0.87 g.cm$^{-3}$ (± 0.02 g.cm$^{-3}$)</td>
</tr>
<tr>
<td>JSC (Mars-1) after vibration</td>
<td>1.07 g.cm$^{-3}$ (± 0.02 g.cm$^{-3}$)</td>
</tr>
<tr>
<td>JSC (Mars-1) loose porosity</td>
<td>0.54</td>
</tr>
<tr>
<td>JSC (Mars-1) after vibration porosity</td>
<td>0.44</td>
</tr>
<tr>
<td>UK4 particle density</td>
<td>2.72 g.cm$^{-3}$</td>
</tr>
<tr>
<td>UK4 Loose</td>
<td>1.28 g.cm$^{-3}$</td>
</tr>
<tr>
<td>UK4 Vibrated</td>
<td>1.57 g.cm$^{-3}$</td>
</tr>
<tr>
<td>UK4 Loose porosity</td>
<td>0.53</td>
</tr>
<tr>
<td>Uk4 Vibrated porosity</td>
<td>0.42</td>
</tr>
</tbody>
</table>
Figure 44: Penetration experiments into the UK4 simulant, results extrapolated from 20 cm up to 50 cm for several simulant bulk densities.
7.1.3 Mechanical Properties of the Lunar Regolith

The lunar Self Recording Penetrometer (SRP) was used on several of the Apollo missions to help characterize the mechanical properties of the near surface lunar regolith by measuring the applied force on the instrument as a function depth (Figure 45). In much the same way as a tradition terrestrial penetrometer functions, the SRP instrument contains a spike-like structure that is pushed into the lunar surface by an astronaut. The final force and depth reached by the instrument were recorded for several locations on the lunar surface. Table 11 shows the results from this series of experiments, along with several other columns of data that have been derived from the original recorded data. (adapted from (Heiken & Vaniman, 1991)). To allow a fair comparison of stresses at the various locations that were investigated on the lunar surface, all stresses have been extrapolated to a depth of 50 cm below the surface. At this depth, the location of the hardest to penetrate regolith was sampled by Apollo 15 SRP index 4. This experiment only penetrated to a depth of 5.2 cm and required a force of 111 N. The surface area diameter of this particular penetrometer was 2.3 cm extrapolating these results to 50 cm and converting to a stress gives approximately 3298 kPa of stress. As previously discussed, in reality, the mechanical properties of the any regolith on a planetary surface can be highly localized and we have seen by analyzing the SRP experiments, and returned core samples (Heiken & Vaniman, 1991), bulk density, porosity and grain size distribution can vary greatly as a function of not only location but also depth (Heiken & Vaniman, 1991) Table 12.
Figure 45: The lunar Self-Recording Penetrometer used on several of the Apollo missions. The instrument is held vertically with the flat, rectangular pad being in contact the surface. The astronaut pushes the penetrometer into the surface, and the force is recorded (source of image is (Heiken, Vaniman, & French, 1991)).
Table 11: Results from the Apollo mission’s Self-Recording Penetrometer instrument (shown above, table created from data taken from (Heiken et al., 1991))

<table>
<thead>
<tr>
<th>Apollo Mission</th>
<th>SRP Index</th>
<th>Probe Diameter</th>
<th>Depth Reached</th>
<th>Force to Depth</th>
<th>Base Area (cm$^3$)</th>
<th>Stress (kPa)</th>
<th>Stress to 50 cm (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>2</td>
<td>2.03</td>
<td>8.2</td>
<td>111</td>
<td>3.24</td>
<td>343</td>
<td>2091</td>
</tr>
<tr>
<td>15</td>
<td>3</td>
<td>2.03</td>
<td>10.2*</td>
<td>111*</td>
<td>3.24</td>
<td>343</td>
<td>1681</td>
</tr>
<tr>
<td>15</td>
<td>4</td>
<td>2.03</td>
<td>5.2</td>
<td>111</td>
<td>3.24</td>
<td>343</td>
<td>3298</td>
</tr>
<tr>
<td>15</td>
<td>5</td>
<td>2.03</td>
<td>11.2*</td>
<td>111*</td>
<td>3.24</td>
<td>343</td>
<td>1531</td>
</tr>
<tr>
<td>16</td>
<td>5</td>
<td>2.03</td>
<td>21.3</td>
<td>215</td>
<td>3.24</td>
<td>664</td>
<td>1531</td>
</tr>
<tr>
<td>16</td>
<td>6</td>
<td>1.28</td>
<td>74</td>
<td>53.5</td>
<td>1.29</td>
<td>416**</td>
<td>281</td>
</tr>
<tr>
<td>16</td>
<td>7</td>
<td>1.28</td>
<td>46</td>
<td>215</td>
<td>1.29</td>
<td>1671</td>
<td>1816</td>
</tr>
<tr>
<td>16</td>
<td>8</td>
<td>1.28</td>
<td>73</td>
<td>199</td>
<td>1.29</td>
<td>1546</td>
<td>1059</td>
</tr>
<tr>
<td>16</td>
<td>10</td>
<td>2.03</td>
<td>22</td>
<td>&gt;215</td>
<td>3.24</td>
<td>664</td>
<td>1510</td>
</tr>
<tr>
<td>16</td>
<td>11</td>
<td>1.28</td>
<td>50.5</td>
<td>&gt;215</td>
<td>1.29</td>
<td>1671</td>
<td>1654</td>
</tr>
<tr>
<td>16</td>
<td>12</td>
<td>1.28</td>
<td>42</td>
<td>&gt;215</td>
<td>1.29</td>
<td>1671</td>
<td>1989</td>
</tr>
<tr>
<td>16</td>
<td>13</td>
<td>1.28</td>
<td>62.5</td>
<td>199</td>
<td>1.29</td>
<td>1546</td>
<td>1237</td>
</tr>
</tbody>
</table>

*Best guess by NASA due to equipment malfunctions. **Estimated by astronaut

Table 12: Lunar regolith data, adapted from (Heiken & Vaniman, 1991)

<table>
<thead>
<tr>
<th>Average bulk density (g.cm$^{-3}$)*</th>
<th>Depth range (cm)</th>
<th>Porosity</th>
<th>Void Ratio**</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>0 - 15</td>
<td>52%</td>
<td>1.07</td>
</tr>
<tr>
<td>1.58</td>
<td>0 - 30</td>
<td>49%</td>
<td>0.96</td>
</tr>
<tr>
<td>1.66</td>
<td>0 - 60</td>
<td>46%</td>
<td>0.78</td>
</tr>
<tr>
<td>1.74</td>
<td>30 - 60</td>
<td>44%</td>
<td>0.87</td>
</tr>
</tbody>
</table>

* ± 0.05 g.cm$^{-3}$, **± 0.07
7.1.4 Anticipated Penetration Forces

Experiments conducted by the Apollo missions on the lunar surface indicate a maximum stress of approximately 3300 kPa to penetrate to a depth of 50 cm. Results from experimental and numerical investigation into the Martial mechanical simulant UK4 indicate a maximum stress of approximately 5305 kPa. In the final probe configuration for this research the probe has a cross sectional area of 16.3×6 mm, which corresponds to a surface area of 0.978 cm². A stress of 5,305 kPa applied to this surface area produces a force of approximately 518.8 N

A lander, rover, or human, unless anchored in place, would not be able to provide a penetration force greater than their weight without the risk of tipping or losing contact with the planetary surface. The weight of the craft/ person provides the downward force and is dependent upon their mass and the gravity of the planetary body they are on. Assuming a force of 519N is needed, we can easily see (Table 13) that the Mars Science laboratory (MSL) has enough weight to easily apply this much without a risk of tipping the rover. In comparison, an astronaut on Mars simply does not have enough weight to provide the needed force to the probe. We can reduce the needed force by reducing the penetration depth, or reducing the cross sectional area of the probe. As shown in the table, the Mars Exploration Rover would require it to utilize 76% of its weight to penetrate the probe to a depth of 50 cm. In reality, mission designers would not want to risk a probe potentially tipping the rover, or getting stuck as it is pushed into the subsurface.
Table 13: A comparison of varies deployment mechanisms for the OPRA probe. The last column shows the percent of the total weight of the deployment mechanism to penetrate the probe to a depth of 50 cm. Here we see that the MSL would only require 16% of its weight while an unanchored astronaut on Mars would not have enough weight to penetrate the probe completely.

<table>
<thead>
<tr>
<th>Deploying Mechanism</th>
<th>Mass (kg)</th>
<th>Target</th>
<th>Gravity (m/s²)</th>
<th>Weight (N)</th>
<th>% Weight Needed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Astronaut</td>
<td>80</td>
<td>Moon</td>
<td>1.62</td>
<td>130</td>
<td>400%</td>
</tr>
<tr>
<td>Astronaut</td>
<td>80</td>
<td>Mars</td>
<td>3.69</td>
<td>295</td>
<td>176%</td>
</tr>
<tr>
<td>Astronaut</td>
<td>80</td>
<td>Earth</td>
<td>9.81</td>
<td>785</td>
<td>66%</td>
</tr>
<tr>
<td>Viking Lander</td>
<td>572</td>
<td>Mars</td>
<td>3.69</td>
<td>2111</td>
<td>25%</td>
</tr>
<tr>
<td>Mars Exploration Rover</td>
<td>185</td>
<td>Mars</td>
<td>3.69</td>
<td>683</td>
<td>76%</td>
</tr>
<tr>
<td>Mars Science Laboratory (MSL)</td>
<td>899</td>
<td>Mars</td>
<td>3.69</td>
<td>3317</td>
<td>16%</td>
</tr>
</tbody>
</table>

7.2 Probe Housing

7.2.1 Window Dimensions

All windows will have a diameter of 4.3 mm and will be 1 mm thick, the same thickness as the probe housing which is discussed in the next section. The window diameter is a direct result of geometric investigation into light rays path as it leaves the end of the optical fiber at the center of the FOB and propagates through the 2 mm right angle prism which is coupled to the 1 mm thick window, as shown in Figure 46. As previously discussed, the NA of all of these fibers is 0.53 which results in an exit angle from the fibers transmitting the signal of approximately 32°, as shown in Figure 46. For this structural analysis work, it will be assumed that the windows
provide no structural support to the probe housing i.e. windows will be left as circular holes in the housing. This assumption is based on the much smaller strain to failure for the window material compared to titanium so the windows could not be safely expected to bear any significant stress.

7.2.2 Housing Dimensions

The probe housing will be of dimension 16.3 × 6.0 mm composed of 1 mm thick titanium as shown in Figure 47. This figure shows a probe of 300 mm in length containing a total of 12 windows; the front wall of the housing contains the first 6 windows that are equally spaced, starting 30 mm from the bottom of the probe wall, at a distance of 40 mm. The rear housing wall contains 6 windows starting 10 mm from the bottom of the housing wall and equally spaced at 40 mm. Each window is horizontally offset from the one below by 2 mm. Each window has a diameter of 4.3 mm. The limiting factor in determining the total number of windows to include in the probe is the cross sectional area as shown in the top view of the figure. Here we note that each FOB occupies a circular area of diameter 2 mm (Figure 47ii). The probe, once assembled will have vertical sampling resolution of 20 mm. This image does not show the spike at the bottom of the probe, nor does it show how the probe will be mounted to the deploying mechanism. In the case of a robotic lander or Rover, a robotic arm could be used to push the instrument into the subsurface. It was beyond the scope of this research to design the attachment mechanisms, but it is assumed that the force will be evenly distributed across the top of the probe housing.
7.3 Structural Analysis

Structural analysis is concerned with investigating either experimentally or numerically, how a structure survives the expected stresses and strains it will be exposed to over its operational lifetime. The probe housing provides two main functions. Firstly, to transfer the mechanical load from the driving force to the regolith, i.e. to move the regolith out of the way, and secondly, to act as a barrier between the regolith and the interior of the probe. FEA was used to numerically verify that the probe housing (detailed in the next section) would survive the anticipated stresses and strains and to help set an absolute limit on the force that could be applied before the structural integrity was breached. AutoCAD Mechanical 2011 FEA software was used to help validate the final probe design. This is in no way meant to represent a comprehensive numerical analysis of the structure, but will allow for any major design problems to be quickly identified. The load will be applied vertically to the probe across the top of the probe housing and it is assumed that the load will be distributed to the probe housing evenly.
Figure 46: i) Top down illustration, and ii), side illustration of two light rays propagating through a FOB, prism, window system. iii) Is a picture of a FOB coupled to a prism.
Figure 47: Illustration of front and rear housing, all units are in mm. This configuration gives a vertical window spacing of 20 mm.
Housing thickness of 1 mm gives a total cross sectional surface area of probe housing of 40.6 \text{ mm}^2 (the perimeter of the cross sectional surface area), which results in a force per \text{ mm}^2 of probe housing of $519 \div 40.6 = 12.8 \text{ N/mm}^2$. The front and rear housing both have a cross sectional surface area of 16.3 \text{ mm}^2 which results in a total force of $12.8 \times 16.3 = 209 \text{ N}$. The total length of the probe (excluding tip) used here was 30 cm. The probe was drawn and analyzed in AutoCAD Mechanical (http://usa.autodesk.com/) which is one of the industry standards for this type of work. This software has the ability to perform FEA on any structure created within the program. This is accomplished by populating the virtual structure with a high density mesh grid, and then creating the stress locations and being applied to the structure will be located as shown in Figure 48. Several models were created using various amounts of stress ranging from 2,000 – 20,000 kPa as detailed in next section. In this image the FEA set up for a maximum applied stress of 20,000 kPa being applied to the probe (note, the right most image, is the only one to scale) is seen.

### 7.3.1 Von Mises Stress

There are a number of different ways to quantify the amount of deformation in a structure, for the purpose of this work the yield point and the Von Mises stress will be used. The yield point of a material is the value at which an applied stress would cause permanent deformation within the structure. In reality, structures can undergo stresses in all of the three dimensions; the Von Mises stress combines all these stresses into a single value for each point within the structure. The Von Mises stress limit is the value at which permanent deformation would occur. The natural choice for the probe housing material is titanium which is 60% more dense than aluminum but almost twice as strong; it is very inert, and has a relatively high melting point (1650°C). Titanium was
selected from the list of materials in the AutoCAD FEA software and is described as having a Von Mises stress limit of 276 MPa.

It is assumed that the probe will be inserted perpendicular into the target regolith with the force applied to the top of the housing and the tip was assumed to be up against a fixed and immovable surface. In reality, the tip of the probe will be moving and the force on the probe will be used to move material out of the way, and to overcome any friction the probe may encounter as it penetrates. This means, in actual fact, the stresses and strains highlighted in this FEA work represent the worst case scenario of a probe encountering an immovable object, such as a rock, or an ice layer below the surface. In reality, mission designers would likely incorporate some type of feedback system that would stop driving the probe into the ground once too much resistant was felt to prevent motor damage or the probe becoming stuck.

7.3.2 Finite Element Analysis: Results

The critical Von Mises stress for titanium is around 276 N/mm², this value represents the structural stress limit. Results from this FEA work indicate that this probe configuration, can easily withstand a stress of 5305 kPa that would result from a force of 518.8 N. Table 14 shows the results from several FEA’s performed on the same housing design, but with various amounts of applied stress from a low of 2000 kPa to a high of 20,000 kPa. The maximum Von Mises stress indicated in each model is recorded in the table below. Even at a stress of almost four times the predicted stress derived from the mechanical simulations in the UK simulant, probe structural integrity is maintained. The maximum Von Mises stress recorded was around is 161
N/mm\(^2\) which is around 58\% of the maximum Von Mises limit stress for titanium. Figure 49 shows the Von Mises results represented graphically, for the front housing of the probe under the maximum applied stress 20,000 kPa.

Table 14: Results from several finite element analysis models. The maximum Von Mises stress Titanium can withstand is 276 N.mm\(^2\). Even at 20,000 kPa we are well below the structural limit.

<table>
<thead>
<tr>
<th>Applied Stress (kPa)</th>
<th>Total Force On Probe (N)</th>
<th>Force on Single Wall (N)</th>
<th>Max Von Mises Stress (N/mm(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>2,000</td>
<td>196</td>
<td>79</td>
<td>16</td>
</tr>
<tr>
<td>5,305</td>
<td>519</td>
<td>209</td>
<td>43</td>
</tr>
<tr>
<td>8,000</td>
<td>782</td>
<td>314</td>
<td>65</td>
</tr>
<tr>
<td>16,000</td>
<td>1565</td>
<td>628</td>
<td>129</td>
</tr>
<tr>
<td>20,000</td>
<td>1956</td>
<td>785</td>
<td>161</td>
</tr>
</tbody>
</table>
Figure 48: Finite element mesh applied to probe housing wall. Here is a wall under a total load of 785.7 N which equates to 48.2 N/mm² of probe housing. These images are taken from a total applied stress of 20,000 kPa model shown in below table. For comparison we see a scaled and a not to scale image side by side.
Figure 49: Graphically represented results of the finite element analysis model for an applied probe stress of 20.000 kPa. Here we note that the maximum Von Mises stress is 162 which is well within Titanium’s Von Mises limit of 276 N/mm².
Figure 50: Graphically represented results of the finite element analysis model for an applied probe stress of 20,000 kPa. Here we view the lowest probe windows on both the front and rear housing.
7.4 Discussion

By analyzing data obtained from lunar Self Recording Penetrometer experiments conducted via the Apollo missions we were able to determine the “worst case” scenario encountered whilst penetrating into the lunar regolith. These results were then extrapolated to a probe with a cross sectional surface area of the OPRA probe. The same methodology was also applied to results obtained from a research group investigating the Martian mechanical simulant, UK4, to determine the maximum anticipated force needed to penetrate the OPRA probe into the Martian and Lunar regolith.

FEA was then performed on the probe housing, via Autodesk AutoCAD Mechanic software to ensure the 1 mm thick Titanium housing was of realistic thickness and that window locations would not cause structural problems. The results indicated that the titanium housing can easily withstand forces in excess of four times the maximum force that was estimated from data analysis of both the Apollo mission and the mechanical investigations into the Martian mechanical simulant UK4. While regolith properties can be highly localized, using the best available data, we have demonstrated that the probe housing design is feasible.
CHAPTER 8 DISCUSSION AND FUTURE WORK

8.1 Discussion

To date, there has not been an instrument deployed on another moon, asteroid or planet that can spectroscopically explore the near subsurface regolith while preserving any stratigraphy that may be present. This dissertation reported on several design aspects of the OPRA instrument concept to help facilitate this goal.

As reviewed in the first chapter, long-term manned missions need to utilize indigenous resources as much as possible, and this has been identified by NASA as a crucial area of research. To date, only experiments from the Apollo missions were able to provide us with complete, intact cores of a planetary body and these were collected manually. Martian subsurface exploration has been limited to robotic scoops and trenches. The OPRA concept represents a way to facilitate the need for this type of exploration by utilizing optical fibers into a small spike like structure that is connected to a spectrometer housed onboard the deploying spacecraft.

The key components of this instrument are the optical fibers, which have been fully space qualified and flown on multiple missions, the most recent being the MSL mission. The actual fiber optic bundle configuration that OPRA utilizes on each of its windows to transmit and receive the signal to and from the sample has already been space qualified by NASA’s Optoelectronics group. The “six-around-one” configuration we use is the same configuration that was space qualified on the LOLA instrument onboard the Lunar Reconnaissance Orbiter.
mission. Whilst it was outside the scope of this project to space qualify the OPRA probe, chapter 2 demonstrates the reliability and proven track record of space based optical fibers.

The optical train was tested via a series spectral comparison tests taken on several relevant materials similar to those expected to be found on Mars. Spectra obtained with the fiber optic bundle and then compared to base line spectra from standard reflectance spectroscopy with the FTIR unit. As expected, there was a very close match achieved by carefully selecting all the optical components to be optically transparent over the wavelength range of the spectra. Once the optics had been validated, they were integrated into the Andromeda chamber running in Titan simulation mode. Spectra were obtained there at temperatures as low as 93K. Our fiber optic bundles have also been utilized by several other research groups providing the basis for several publications and conference proceedings as covered in Chapter 6.

The final probe design was structurally validated by Finite Element Analysis using Autodesk AutoCAD software. By using the experimental results from the Apollo missions Self Recording Penetrometer experiments and results from investigations into the Martian mechanical analogue simulant a realistic anticipated force was derived. Numerical modeling indicates that 1 mm thick titanium housing could easily tolerate the anticipated forces.

8.2 Future Work

This dissertation takes the TRL of the OPRA instrumentation concept to level 3, which is defined by NASA to be the demonstration either analytically or experimentally the proof of concept of
critical functions of the proposed instrument. In order to take this to a higher TRL level a standalone prototype would need to be manufactured and tested under realistic expected conditions and would need to go through rigorous space qualification testing.

The OPRA instrumentation concept fulfills NASA’s need for continued subsurface exploration and is relatively simple, and inexpensive, when compared to complex corers, drills and excavators. Due to the robustness, flexibility and scalability of a “spike like” fiber optic instrument, it could easily be incorporated onto the end of a robotic arm or even into a standalone instrument to be used by an astronaut.


Appendix 1

Tables, Plots and Code
Appendix 1.1
Fiber Optic Bundle Characteristics (Plots)

Probe Distance 0mm, sigma=0.445mm

Probe Distance 0.5mm, sigma=0.441mm

Probe Distance 1mm, sigma=0.5mm

Probe Distance 2mm, sigma=0.684mm

Probe Distance 2.5mm, sigma=0.75mm

Probe Distance 3mm, sigma=0.968mm

Wavefront Sensor
Probe Distance 3.5mm, sigma=1.045mm

Probe Distance 4.5mm, sigma=1.192mm

Probe Distance 6mm, sigma=1.306mm

Probe Distance 7mm, sigma=1.313mm

Probe Distance 5mm, sigma=1.168mm

Probe Distance 7.5mm, sigma=1.218mm

Probe Distance 7.5mm, sigma=1.218mm
Appendix 1.2

Numerical Model Core MatLab Code

% code to model fiber optic probe Pre run Variables
clear all; clc ; tic
[In_Variables, headertext] = xlsread('Code_Inputs.xls', 'Variable_Input');
%user spreadsheet located in same folder as program to read in variables

; %Set Up===============================================================
Total_Number_of_Models=In_Variables(1,1)
%this is the number of models that have been defined in the spreadsheet
array_config_case=In_Variables(3,1)
sample_grid_res=In_Variables(5,1) %Sample grid resolution
rec_grid_res=In_Variables(7,1) %Receiving fibers grid resolution
%
=====================================================================

dsample_min=In_Variables(9,1) %start sample distance
dsample_max=In_Variables(11,1) %end sample distance
dsample_high_res_distance=In_Variables(13,1)
%high res distance, close to sample we want very small changes in distance
%as this is the most sensitive area, as we move away, we can reduce resolution

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
dsample_high_res_step_count=In_Variables(15,1)
%how many steps between dsample min and dsample_high_res_distance
dsample_low_res_step_count=In_Variables(17,1)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
dsample_total_steps=dsample_high_res_step_count+dsample_low_res_step_count
%total number of steps

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
dsample_high_res_step_size=(dsample_high_res_distance-dsample_min)/dsample_high_res_step_count
dsample_low_res_step_size=(dsample_max-dsample_high_res_distance)/dsample_low_res_step_count

for Current_Model_Run=1:Total_Number_of_Models;
; %Physical Properties
num_rec_fibers=In_Variables(Current_Model_Run,3);
%how many receiving fibers
fiber_separation= In_Variables(Current_Model_Run,4)
% microns, this is core center to core center between 2 fibers
rec_core_diam= In_Variables(Current_Model_Run,5); %microns
rec_clad_diam= In_Variables(Current_Model_Run,6); %microns

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rec_NA= In_Variables(Current_Model_Run,7); %no units
trans_core_diam=In_Variables(Current_Model_Run,8); %microns
trans_clad_diam=In_Variables(Current_Model_Run,9); %microns
trans_NA=In_Variables(Current_Model_Run,10); %no units
%derived from above
area_600_micron=pi*300^2;
%standard is based around a 600 micron diamter fiber
power_from_send_fiber=(pi*(trans_core_diam/2)^2)/area_600_micron;
%scales power to surface area in relation to a 600 micron fiber power
%ie a 600micron fiber send power will be 1

;%Unit conversions======
rec_core_diam=rec_core_diam/1000; %=from mm to microns
rec_clad_diam=rec_clad_diam/1000; %=from mm to microns
trans_core_diam=trans_core_diam/1000; %=from mm to microns
trans_clad_diam=trans_clad_diam/1000; %=from mm to microns
fiber_separation=fiber_separation/1000; %=from mm to microns

;set up sample grid array
sample_grid=[sample_grid_res,sample_grid_res,5];
% sample_grid[,,1]=x
% sample_grid[,,2]=y
% sample_grid[,,3]=illum FLAG
% sample_grid[,,4]=samp_illum_cross_over_flag
% sample_grid[,,5]=
;Set Up Receive Grid
rec_grid_step_size=rec_core_diam/rec_grid_res;
%set the sample grid to a tight square around the illumination area
rec_grid = [rec_grid_res,rec_grid_res,5]; %this is all results in one multi dim array
illum_flag_rec_grid=[sample_grid_res, sample_grid_res];
% rec_grid[,,1]=x
% rec_grid[,,2]=y
% rec_grid[,,3]=illum FLAG
% rec_grid[,,4]=x_map to sample grid
% rec_grid[,,5]=y map to sample grid
% rec_grid[,,6]=total_power from all cross over sample grid points
populate Receive grid with x y and illum flag
%dcount=0; %count of number of sample distances run
dsample=dsample_min-dsample_high_res_step_size;
stack_samp_illum_cross_over_flag=zeros(sample_grid_res);
for dcount=1:dsample_total_steps;
    if dcount<=dsample_high_res_step_count;
        dsample=dsample+dsample_high_res_step_size
    else;
        dsample=dsample+dsample_low_res_step_size
    end;

% input('dsample')
[pdf_function,tot_pdf_at_d]=calculate_transmit_flux(array_config_case, fiber_separation, trans_NA, rec_NA, num_rec_fibers, dsample, sample_grid_res);

; %set up rec grid
y=rec_core_diam/2; %this is max rec grid height
for I =1:rec_grid_res;%move down the grid
    x=-(rec_core_diam/2);
    %this sets up loop to start at far left of grid. zero is center of fiber
    for j=1 : sample_grid_res; %move across the grid
        rec_grid(i,j,1)=x;
        rec_grid(i,j,2)=y;
        if (((x^2)+y^2)^0.5)< rec_core_diam/2;
            rec_grid(i,j,3)=1;
        %this grid is square in shape when in fact the fiber is round,
        %this corrects for this and flags only "active" points
        else sample_grid(i,j,3)=0;
        end
        x=x+rec_grid_step_size ; %move across to next grid point distance
    end;
    y=y-rec_grid_step_size; %move down to next grid point distance
end;
;% Set up Sample Grid

%define max illum radius NA =sin(angle)
illum_r_max=dsample*tan(asin(trans_NA)); %is a function of dist from probe tip
illum_area=pi*illum_r_max^2;
sample_grid_step_size=(2*illum_r_max)/sample_grid_res;
%sample grid grid around illum area only
sample_grid_step_area=(sample_grid_step_size)^2; %actual physical surface area
flux_at_send_fiber=1;
%power_from_send_fiber/sample_grid_step_area; %units of power/mm^2
rec_grid_step_area=(rec_grid_step_size)^2;
%move thios to a more logical position in code
%populate sample_grid probe is at center
y=illum_r_max;
for I=1:sample_grid_res; %populate sample grid with x y illum flag
    x=-illum_r_max;
    for j=1:sample_grid_res;
        sample_grid(i,j,1)=x;  %x
        sample_grid(i,j,2)=y;  %y
        if (((x^2)+y^2)^0.5)< illum_r_max;
            sample_grid(i,j,3)=1;  % illum flag
        else sample_grid(i,j,3)=0;
        end;
        x=x+sample_grid_step_size;
    end;
    y=y-sample_grid_step_size;
end;

%set up rec_area on samp grid
y=illum_r_max;
for I=1:sample_grid_res; %populate sample grid with illum rec cross over area flag
    for j=1:sample_grid_res;
        x_rec_pos_mapped_to_samp_grid=sample_grid(i,j,1)-fiber_separation;
        dist_to_point=abs((x_rec_pos_mapped_to_samp_grid^2)+y^2)^0.5;
        if dist_to_point<=illum_r_max;
            sample_grid(i,j,4)=1;
            sample_grid(i,j,5)=x_rec_pos_mapped_to_samp_grid;
            sample_grid(i,j,6)=y;
        else sample_grid(i,j,4)=0;
        end;
    end;
    y=y-sample_grid_step_size;
end;

%=====================================================%
%calculate distance from samaple grid point to rec grid point and sum up all flux

for I=1:rec_grid_res;
    for j=1:rec_grid_res;
        total_power_at_rec_grid_point=0;
        power_in_sample_grid_area=pdf_function;
        for k=1:sample_grid_res;
            if sample_grid(i,j,4);
                g=rec_grid(i,j,1);
            else sample_grid(i,j,4)=0;
            end;
            if sample_grid(i,j,4);
                g=rec_grid(i,j,1);
            else sample_grid(i,j,4)=0;
            end;
            x=abs(rec_grid(i,j,1)-sample_grid(k,l,1));
            y=abs(rec_grid(i,j,2)-sample_grid(k,l,3));
            rec_grid(i,j,4)=x;
            rec_grid(i,j,5)=y;
            if sample_grid(i,j,4);
                if samp_illum_cross_over_flag = 1 then do;
                    g=rec_grid(i,j,1);
                end;
            else sample_grid(i,j,4)=0;
            end;
        end;
        total_power_at_rec_grid_point=total_power_at_rec_grid_point+power_in_sample_grid_area;
    end;
end;

%=====================================================%
gg = sample_grid(k, l, 1);
xy_plane_distance = (x^2 + y^2)^0.5;
xyz_distance = (xy_plane_distance^2 + dsample)^0.5;

flux_up_at_rec_grid_point = power_in_sample_grid_area(i, j) / ((4*pi*xyz_distance^2)/2); % half surface area of a sphere
power_up_at_rec_grid_point = flux_up_at_rec_grid_point * rec_grid_step_area;
% flux * area = total power

total_power_at_rec_grid_point = total_power_at_rec_grid_point + power_up_at_rec_grid_point;
% no need to save each individual distance and flux just sum
% all contributions and store this sum
else continue;
end;
end;
rec_grid(i, j, 6) = total_power_at_rec_grid_point;
% once all cross over illum points are summed save results in
% move to next point
end;
end;

%———————————————————
% Begin extraction ————
% separate multi dimension arrays to series of 2d arrays ————
%———————————————————

x_rec_grid = [rec_grid_res, rec_grid_res];
y_rec_grid = [rec_grid_res, rec_grid_res];
illum_flag_rec_grid = [rec_grid_res, rec_grid_res];
power_received_at_rec_grid_points = [rec_grid_res, rec_grid_res];
for i = 1: rec_grid_res;
    for j = 1: rec_grid_res;
        x_rec_grid(i, j) = rec_grid(i, j, 1);
        y_rec_grid(i, j) = rec_grid(i, j, 2);
        illum_flag_rec_grid(i, j) = rec_grid(i, j, 3);
        rec_xmap_to_sample(i, j) = rec_grid(i, j, 4);
        rec_ymap_to_sample(i, j) = rec_grid(i, j, 5);
        power_received_at_rec_grid_points(i, j) = rec_grid(i, j, 6);
    end;
end;

total_power_for_all_rec_points = sum(sum(power_received_at_rec_grid_points)) * num_rec_fibers;
%define sample_grid 2d extraction arrays
x_sample_grid=[sample_grid_res,sample_grid_res];
y_sample_grid=[sample_grid_res,sample_grid_res];
illum_flag_sample_grid=[sample_grid_res,sample_grid_res];
for I=1:sample_grid_res;
    for j=1:sample_grid_res;
        x_sample_grid(i,j)=sample_grid(i,j,1);
        y_sample_grid(i,j)=sample_grid(i,j,2);
        illum_flag_sample_grid(i,j)=sample_grid(i,j,3);
        samp_illum_cross_over_flag(i,j)=sample_grid(i,j,4);
    end;
end;
%convert arrays to needed precisions
%integer arrrays

% x_rec_grid=int8(x_rec_grid);
% y_rec_grid=int8(y_rec_grid);
illum_flag_rec_grid=int8(illum_flag_rec_grid);

% x_sample_grid=int8(x_sample_grid);
% y_sample_grid=int8(y_sample_grid);
illum_flag_sample_grid=int8(illum_flag_sample_grid);
samp_illum_cross_over_flag=int8(samp_illum_cross_over_flag);

stack_illum_surface_area(dcount)=sample_grid_step_area*sum(sum(samp_illum_cross_over_flag));
%calculate SA of cross over
stack_illum_area(dcount)=illum_area;
stack_illum_diameter(dcount)=illum_r_max*2; %diamter of spot
stack_dsamp(dcount)=dsample; %used to store each sample distance
stack_total_power_at_rec_grid_points(dcount)=total_power_for_all_rec_points;
samp_illum_cross_over_flag=samp_illum_cross_over_flag+illum_flag_sample_grid;
%so we have non illum and illum on one matrix
stack_samp_illum_cross_over_flag=[stack_samp_illum_cross_over_flag;samp_illum_cross_over_flag];

tot_pdf_flux(dcount)=tot_pdf_at_d;
%put input variables into an array this makes it easier when putting data in excel
% 10 is just a numnber large enough to fit all variables in aray expand when needed
run_time=toc
dcount
end
%save variable names and values
% s=10;
% variable_list_value={s};
% variable_name={s};

variable_name{1}= 'num_rec_fibers'; variable_list_value{1}=num_rec_fibers;
variable_name{2}= 'fiber_separation'; variable_list_value{2}=fiber_separation;
variable_name{3}= 'rec_core_diam'; variable_list_value{3}=rec_core_diam;
variable_name{4}= 'rec_clad_diam'; variable_list_value{4}=rec_clad_diam;
variable_name{5}= 'rec_NA'; variable_list_value{5}=rec_NA;

variable_name{6}= 'trans_core_diam'; variable_list_value{6}=trans_core_diam;
variable_name{7}= 'trans_clad_diam'; variable_list_value{7}=trans_clad_diam;
variable_name{8}= 'trans_NA'; variable_list_value{8}=trans_NA;

variable_name{9}=power_from_send_fiber;variable_list_value{9}=power_from_send_fiber;

variable_name{10}='------------------------';variable_list_value{10}='------------------------';
variable_name{11}='Start distance'; variable_list_value{11}=dsample_min;
variable_name{12}='End Distance';
variable_list_value{12}=dsample_max;
variable_name{13}='High Res <';
variable_list_value{13}=dsample_high_res_distance;
variable_name{14}='High Res Step Size';
variable_list_value{14}=dsample_high_res_step_size;
variable_name{15}='Number of High Res Steps';
variable_list_value{15}=dsample_high_res_step_count;
variable_name{16}='Low Res Step Size';
variable_list_value{16}=dsample_low_res_step_size;
variable_name{17}='Number of Low Res Steps';
variable_list_value{17}=dsample_low_res_step_count;
my_variables=[variable_name', variable_list_value'];

%save results for export to excel
results_name{1}= 'Sample Distance (mm)';
results_name{2}= 'Illumination Surface Area (mm^2)';
results_name{3}= 'Illumination Spot Diamter';
results_name{4}= 'Cross Over Surface Area (mm^2)';
results_name{5}= 'Total Returned Power';

my_results(Current_Model.Run,:,1)=stack_dsample;
my_results(Current_Model.Run,:,2)=stack_illum_area;
my_results(Current_Model.Run,:,3)=stack_illum_diameter;
my_results(Current_Model.Run,:,4)=stack_illum_surface_area;
my_results(Current_Model.Run,:,5)=stack_total_power_at_rec_grid_points;
my_results(Current_Model.Run,:,6)=Current_Model_Run;
my_results(Current_Model_Run,:,:)=[tot_pdf_flux];
% use code below to plot a section of results
% plot(stack_dsamp,count),total_power_at_rec_grid_points)
%my_results(Current_Model_Run,:,6)=[];
% my_results(Current_Model_Run,:,7)=[];
% my_results(Current_Model_Run,:,8)=[];
% my_results(Current_Model_Run,:,9)=[];
% my_results(Current_Model_Run,:,10)=[];
% my_results(Current_Model_Run,:,11)=[];
% my_results(Current_Model_Run,:,12)=[];
%
%plot(stack_dsamp,stack_total_power_at_rec_grid_points);
%quick plot of power v distance from probe
% results_name{5}='rec NA'; results_list_value{5}=rec NA;
% results_name{6}='trans_core_diam';results_list_value{6}=trans_core_diam;
% results_name{7}='trans_clad_diam';results_list_value{7}=trans_clad_diam;
results_list_value{8}='trans NA'; results_list_value{8}=trans NA;
%Below code is used to produce plots if and when needed
% % reduced arrays to either a 1 or 0 flag this helps plot arrays
% a=sample_grid(:,:,3)/sample_grid(:,:,3);
% ind=find(isnan(a)); a(ind)=0; %remove nan caused by 0/0
% b=sample_grid(:,:,4)/sample_grid(:,:,4);
% ind=find(isnan(b)); b(ind)=0; %remove nan caused by 0/0
% figure
% axis square; view(2);hold
% surf(a)
% title('Sample Grid Illum Area')
% %------------------------------------------------------------------
% figure
% axis square; view(2);hold
% surf(b)
% title('Sample Grid Cross Over Area')
% %------------------------------------------------------------------
% figure
% axis square; view(2);hold
% c=a+b;
% surf(c);
% title('Sample Grid Illum/Cross Over Area')
end;
% this is end of model number loop
%my_results=my_results';
save my_results.mat my_results;
Appendix 1.3

Other Research Validating FOB.

List of publications validating the FOB adapted for other projects, for use by other members of the space center:

**Key:**  
**ASR:** Advances in Space Research, **LPSC** Lunar & Planetary Space Conference  
**EPSC-DPS** European Planetary Science Congress - Division of Planetary Sciences

1. **A FACILITY FOR SIMULATING TITAN'S ENVIRONMENT**  
ASR 2012 (F. C. Wasiak et al., 2012)

2. **SPECTRAL PROPERTIES OF DECCAN PALAEOSOLS, INDIA: IMPLICATIONS FOR THERMALLY ALTERED PHYLLOSILICATES ON MARS**  
LPSC 2012 (Gavin & Senousy, 2011)

3. **INFRARED MONITORING OF LIQUID/SOLID HYDROCARBONS UNDER TITAN SIMULATED CONDITIONS**  
LPSC 2012 (Cornet & Magar, 2012)

4. **NUMERICAL MODELING AND OPTIMIZATION OF BUNDLED FIBER OPTIC FTIR PROBES FOR SPECTROSCOPY OF SMALL TARGETS**  

5. **A TITAN SIMULATION CHAMBER**  

6. **MEASURING EVAPORATION RATES OF LIQUID METHANE UNDER TITAN SIMULATED CONDITIONS**  
LPSC 2011 (Cornet, Wasiak, Welivitiya, Chevrier, & Roe, 2011)

7. **MEASURING EVAPORATION RATES OF METHANE UNDER SIMULATED TITAN CONDITIONS**  
LPSC 2011 (Luspay-Kuti, Wasiak, Chevrier, Blackburn, & Roe, 2011)
8. A FACILITY FOR SIMULATING TITAN’S ENVIRONMENT

9. REFLECTANCE SPECTRA OF LOW-TEMPERATURE CHLORIDE AND
   PERCHLORATE HYDRATES RELEVANT TO PLANETARY REMOTE
   SENSING
   LPSC 2011  (Hanley, Chevrier, & Dalton, 2011)

10. NUMERICAL MODELING OF FIBER OPTIC BUNDLES FOR IN SITU
    REFLECTANCE SPECTROSCOPY

11. EXPERIMENTAL INVESTIGATION INTO THE EFFECTS OF METEORITIC
    IMPACTS ON THE SPECTRAL PROPERTIES OF PHYLLLOSILICATES ON
    MARS
    LPSC 2010  (Gavin, Chevrier, Ninagawa, Gucsik, & Hasegawa, 2010)

13. REFLECTANCE SPECTRA OF LOW-TEMPERATURE CHLORIDE AND
    PERCHLORATE HYDRATES AND THEIR RELEVANCE TO THE MARTIAN
    SURFACE
    LPSC 2010  (Hanley, Chevrier, Davis, Altheide, & Francis, 2010)

14. SPECTRAL ANALYSIS OF DECCAN PALEOSOLS, INDIA: ANALOG FOR
    PHYLLLOSILICATES ON MARS
    LPSC 2010  (Gavin, 2010)

15. SPECTRAL ANALYSIS OF DECCAN PALEOSOLS, INDIA: ANALOG FOR
    PHYLLLOSILICATES ON MARS
    LPSC 2010  (Gavin, 2010)

16. REFLECTANCE SPECTRA OF LOW-TEMPERATURE CHLORIDE AND
    PERCHLORATE HYDRATES AND THEIR RELEVANCE TO THE MARTIAN
    SURFACE
    LPSC 2009  (Davis, Chevrier, & Altheide, 2009)

17. SUBSURFACE SPECTROSCOPIC PROBE FOR REGOLITH ANALYSIS
    (R Pilgrim, Ulrich, & Leftwich, 2009)

18. OPTICAL DESIGN OF OPRA: OPTICAL PROBE FOR REGOLITH ANALYSIS
Appendix 2

Curriculum Vitae
ROBERT PAUL PILGRIM

EXECUTIVE SUMMARY
My degree in Astrophysics has provided me with a very strong science/math/computer programming background; with several real world project experiences, most notably I have worked on a $400,000 NASA funded project for which I was lead graduate student; and a $600,000 life cycle analysis (LCA) project which was the largest carbon footprint analysis project done of its kind in the world to date. Currently I work for the National Office for Research on Measurement and Evaluation Systems (NORMES)

EDUCATION
University of Arkansas  Space & Planetary Sciences (PhD)  2006-2013
Hertfordshire University  Astrophysics (BSc)  2001-2003/2004-2005
Oklahoma University  Exchange student  2003-2004

FUNDING SOURCES
2012-Present  National Office for Research on Measurement and Evaluation Systems: Research Associate
2009-2010  Life Cycle Analysis (LCA) Duties: Data analyst and developing numerical modeling for estimating carbon footprints
2009 & 2008  Upwards Bound Math Teacher (Summer) Duties: Develop lesson plans, evaluate, grade and teach math
2006-2007  Research assistant

ADDITIONAL SKILLS & EXPERIENCES
Computer Platforms: UNIX, Windows
Computer Languages: SAS, FORTRAN, Maple, IDL, SQL
MatLab (working knowledge of mapping and image processing toolbox)
Visual Basic with Applications (VBA)
Computer Tools: Palisade TopRank and @Risk advanced statistical analysis package
Autodesk AutoCad and 3ds Max
Finite Element Analysis (FEA)
Microsoft: Office, Project and Access
Microsoft SharePoint Design

• Level 1000 clean room experience.
• Extensive real world programming and project management.

PUBLICATIONS, CONFERENCES AND PROPOSALS

EDUCATION
University of Arkansas, PhD Space and Planetary Science (2013)
Research: My PhD research has been based around demonstrating the feasibility of a fiber optic subsurface probe as a viable method for planetary subsurface exploration. My research is also highly computational and I have a publication which is based around my numerical modeling.
In addition to the standard requirements to progress on my PhD I have taken considerable steps to develop my transferable skills which I feel are very valuable in today’s job market. I have gained considerable skills and actively pursued project other projects outside of my requirements.

Hertfordshire University, BSc Astrophysics (2005)
This degree program was a highly extensive program that covered not only the fields of physics, astronomy and the physics of the universe, but also was highly computational and involved the use several programming languages

FUNDING SOURCES
Research Associate & Graduate Assistant
SAS programmer and data analyst at the National Office for Research on Measurement and Evaluation Systems (NORMES). NORMES provides analysis of state performance scores on required benchmark state exams and No Child Left Behind Act school evaluations and performance reports. Distributed via the Internet, NORMES makes certain data and reports available on its website for the public, as well as through an authorized, private access portal for educators to view and analyze data and reports. http://www.sas.com/success/univofarkansas.html
Currently I am part of a small team prototyping a new type of online school testing program that has never been done before. This work will be introduced into a small number of schools for beta testing with the final goal of the project being to have a fully marketable product that parallels with current state wide testing practices that will help in teaching in STEM programs.

Data Analyst: Life Cycle Assessment (2009-2010)
I worked 9 months, full time, in another department within the University of Arkansas to be involved in the largest life cycle assessment (LCA) conducted to date (as of 2010) on the US dairy industry. This project was commissioned by US dairy industry, and the principle investigator was Dr. Greg Thoma. I was responsible for data reduction, validation and modeling of several areas of the returned primary datasets. Modeling greenhouse gas emissions and integrating my results with other team members and computational models to help build a detailed carbon footprint from cradle to farm-gate. I was also responsible for developing the uncertainty and sensitivity analysis models for the feed data and waste data for this project. This was achieved by integrating our final computational models with Palisades TopRank and @Risk software.

Proposal Title: Optical Probe for Regolith Analysis (OPRA)
The proposal was submitted to NASA’s Planetary Instrumentation Definition & Development Program (PIDDP) and was selected for funding (PIDDP-NNH06ZDA001N). I worked under principal investigator Dr. Ulrich on this S400K NASA funded project to perform research and development (R&D) on the proposed spectroscopic sub surface reflectance instrumentation. This project encompassed numerous skill sets such as 2D/3D model designs, fiber optics, numerical modeling, finite element analysis of structural designs and spectroscopy. Space Photonics Inc. was the industrial partner on this project. This project was completed to a technology readiness level (TRL) 3

REFERENCES
Dr. Rick Ulrich, Professor, Chemical Engineering University of Arkansas
Email: mrich@uark.edu, Phone: (479) 575-5645

Dr. Sean Mulvenon, Director, National Office for Research on Measurements & Evaluation Systems (NORMES)
Professor, Educational Statistics and Research Methods Curriculum and Instruction University of Arkansas
Email: seann@uark.edu, Phone: (479) 575-5185
Appendix 3  The Law of the Farm

I am not a sheep waiting to be prodded by the shepherd of life; I refuse to talk, to walk or to sleep amongst the sheep, for there disease of complacency is contagious.
I will not hear those who weep and complain, let them join the sheep, the slaughterhouse of underachievement, remorse and regret is waiting for them.
I will persist until I succeed

The prizes of life are near the end of the journey, not the beginning.
It is not given to me to know how many steps are needed to reach my prizes, never will I know unless I turn each let down, turn each disappointment and turn each obstacle that stands in my way, into a chance to develop, so I may progress and turn the corner bringing me closer to the prizes.
I will persist until I succeed

Each day’s effort is but one blow of my blade against the mighty oak.
Each blow of my blade, each day of my life may seem of little consequence at times, but from what may at times seem futile blows, from seemingly insignificant days, comes the eventual fall of the mighty oak, likened to each day of my life, the rewards are inevitable.
I will persist until I succeed

I will not waste days of my life, for each day the oak shall grow back a little, nullifying past efforts.
Each seed of misfortune will carry in it the growth of knowledge and the chance to adapt and improve. Learn the lessons that need to be learned and move on as best I can.
I will persist until I succeed

Never will I allow a single blow of my blade to be wasted, the oak will eventually fall
Never will I allow a single day to be wasted without progression, the prizes are inevitable.
I will persist until I succeed

We reap what we sow.
Each day we sow and maintain the seeds of our own future harvest.

Today I will sow and maintain my harvest….. My harvest will be good…